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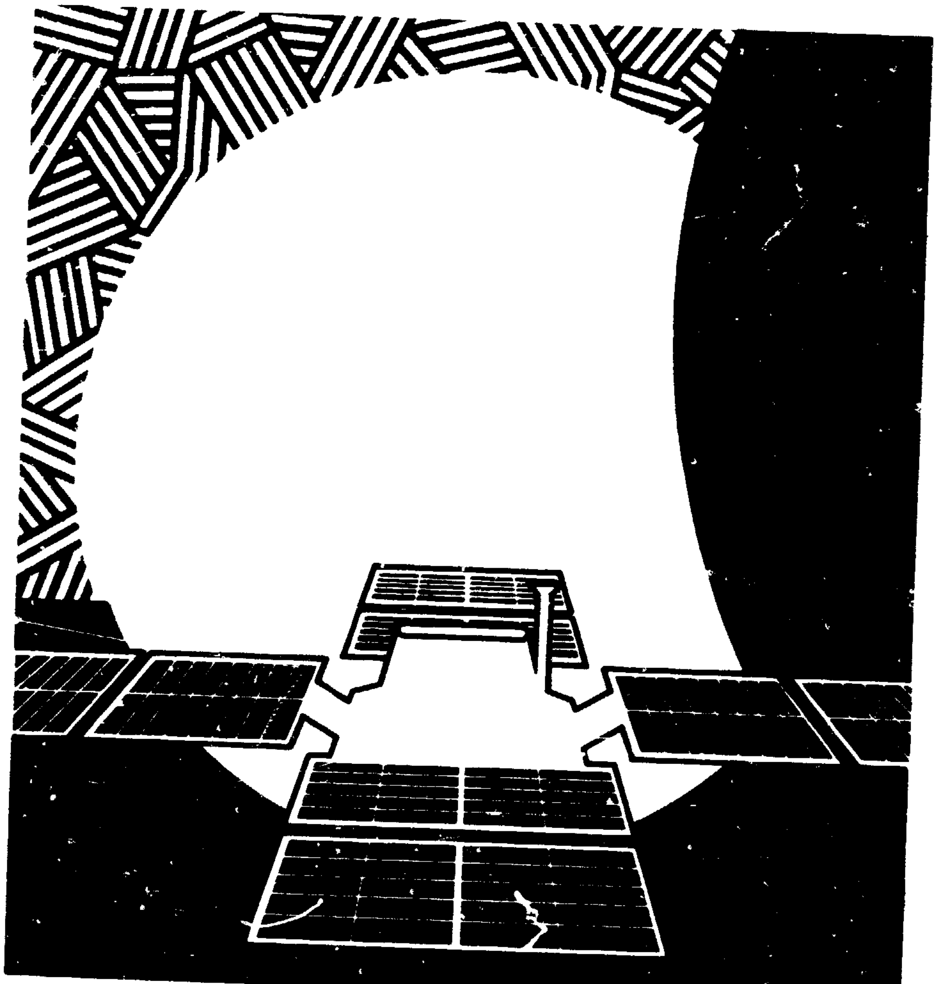
Solar Cell Array Design Handbook

Volume 2



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16. Abstract

The Solar Cell Array Design Handbook is written at a practicing engineering level and provides a comprehensive compilation of explanatory notes, design practices, analytical models, solar cell characteristics, and material properties data of interest to personnel engaged in solar cell array performance specification, hardware design, analysis, fabrication and test.

Twelve handbook chapters discuss the following: historical developments, the environment and its effects, solar cells, solar cell filters and covers, solar cell and other electrical interconnections, blocking and shunt diodes, substrates and deployment mechanisms, material properties, design synthesis and optimization, design analysis, procurement, production and cost aspects, evaluation and test, orbital performance, and illustrative design examples. A comprehensive index permits rapid locating of desired topics.

The handbook consists of two volumes: Volume I is of an expository nature while Volume II contains detailed design data in an appendix-like fashion. Volume II includes solar cell performance data, applicable unit conversion factors and physical constants, and mechanical, electrical, thermal, optical, magnetic, and outgassing material properties. Extensive references are provided.

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SOLAR CELL ARRAY DESIGN HANDBOOK

Volume II

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

This second volume of the Solar Cell Array Design Handbook provides detailed design data. Discussions of this data and the definitions of symbols and units are given in Volume I.

To expedite finding the appropriate general discussions and the detailed design data, the chapters and sections of Volumes I and II are numbered and titled identically with few, but obvious, exceptions. Inasmuch as detailed design data is either not applicable or not available for some of the chapters and sections, corresponding chapters or sections of Volume II simply do not exist.

VOLUME II

CONTENTS

(Note: The topical contents of the chapters and sections in Volume II are identical to those of Volume I.)

CHAPTER 1

QUALITY OF DATA

CONTENTS

CHAPTER 1

QUALITY OF DATA

The detailed design and test data included in this second volume of the Solar Cell Array Design Handbook are believed to be the best data currently available. In order to select the best from all the data that were collected for possible use in this handbook, a data quality-rating scheme was developed and applied to the data on hand; all questionable data were rejected.

The user of the design and test data in this handbook is cautioned that each of the many different sets of data that are included were typically obtained by slightly different test methods and from different test specimens selected from different production lots. None of these differences can be fully ascertained from the available test documents, so that it is not surprising to find that some of the data sets may not be mutually compatible with each other, as would be required, for instance, for comparative analyses and tradeoff studies.

1.1 DATA QUALITY CRITERIA

One of the ground rules for preparing this handbook was to define standards of quality for experimental data, to apply these standards to the data that were collected, and to report only the highest quality data.

The process by which standards of quality for solar cell electrical output data were developed is documented in the following. These standards of quality can be used as a guide to determine the relative importance of certain aspects of a future test program, such as selecting an adequate sample size, establishing the frequency of standard solar cell calibration, and others.

It should be recognized that many of the quality rating factors were based on engineering judgment for the simple reason that at the present time they cannot be obtained otherwise. Some of the rating factors are oversimplifications that were purposely introduced to prevent the rating scheme from becoming overly complicated without introducing errors that would have affected the outcome of the rating significantly.

The following properties of solar cell test data were selected for quality evaluation:

- Test Sample
  - Sample Size
  - Sampling Procedure
  - Manufacturing Date
- Illumination Source
  - Type of Source and Spectrum
  - Intensity Stability
  - Intensity Uniformity
- Calibration Technique
  - Standard Solar Cell
  - Calibration Frequency
- Test Setup
  - Temperature Control
  - Voltage - Pickoff
  - Instrumentation

1.1.1 Sample Size

It is a well recognized fact that increasing the (random) sample size, viz., the number of cells in a test sample selected at random from a population (production lot), will permit a more accurate prediction of the mean behavior of the population. The estimated mean m of the population is always calculated from the measured mean $\bar{x}$ of the sample; however, there is a risk α that the estimated population mean m is off from the true, but unknown mean, by an amount d or greater. Or, conversely, there is $1 - \alpha$ confidence that the estimated population mean is different than the true mean by an amount less than d. If the potential error d is

fixed, the confidence $1 - \alpha$ (or the risk α), depends upon the sample size n and on the standard deviation σ of the population (or the spread in the test data s, if σ is unknown) in accordance with the following relationship:

$$n = \frac{z_p^2 \cdot \sigma^2}{d^2} \qquad (1.1-1)$$

where z_p is the standard normal variable and $p = 1 - \alpha/2$. z_p is given in a statistical table of "Cumulative Normal Distribution Values of z_p."

In order to obtain an estimate of σ to use in Eq. 1.1-1, a number of sets of solar cell test data were reviewed. It was found that the test samples are seldom selected at random from an entire production run and therefore, rarely represent the entire population statistically. However, both the mean and the distribution of the entire population (many production lots) is reasonably well known from the cell manufacturer's quality control records, at least for electrical output under standard test conditions (28°C, one solar constant, AM0). Some recent, large TRW solar cell procurements were designed to encompass the cell manufacturer's yield distribution as follows.

Electrical Group No.	Minimum Output Current at 0.425 V for 0.004 A Intervals
1	0.235 A
2	0.239 A
3	0.243 A
4	0.247 A
5	0.251 A
6	0.255 A
7	0.259 A

Typical calibration and test repeatability is ±0.002 A, or one-half of the interval of an output group. From this the population mean and the standard deviation were estimated to be:

$$m = 0.249 \text{ A}$$

$$\sigma = 0.005 \text{ A}$$

where it was assumed that the 6σ limits ($\pm 3\sigma$) include the entire distribution ranging from 0.235 A to 0.263 A. Knowing m, values of d can be selected corresponding to any desired uncertainty. For example, d = 0.00249 A corresponds to a ±1 percent uncertainty.

Using Eq. 1.1-1, and values for σ, z_p and d, as discussed above, values for confidence $1 - \alpha$ were calculated as a function of sample size n and are plotted in Figure 1.1-1. For a sample size n, Figure 1.1-1 gives the confidence $1 - \alpha$ that the sample mean $\bar{x}$ is off from the population mean by an amount less than d.

Solar cell measurements are usually not assumed to be significantly more accurate than ±1 percent. Consequently, the ±1 percent allowable error curve in Figure 1.1-1 was chosen as the grading scale for sample size n.

1.1.2 Sampling Procedure

To be useful, data must reflect the behavior of the entire population since those using the data will not be selecting cells from the original sample from which the data were taken; rather, the user will be selecting samples from the population at large. In order to make valid, nontrivial generalizations about the population from sample statistics, the sample should be a random sample. A useful type of sampling is defined by the requirement that each individual in the population has an equal chance of being the first member of the sample; after the first member is selected, each of the remaining individuals in the population has an equal chance of being the second member; and so forth. This type of a sample is known as a simple random sample. Experience teaches that it is not safe to assume that a sample selected haphazardly without any conscious plan can be regarded as if it had been obtained by simple random sampling. Frequently, it is assumed that the solar cells in a carton have just as random a distribution as any other sample of cells. However, it is a known fact that average output varies from production lot to production lot and from day to day. Thus, if a carton contains cells that were produced on a given day, then that carton does not contain a random sample by definition since every cell in the population did not have an equal probability of selection.

The highest confidence rating (1.0) was arbitrarily given for well defined random sampling procedures. Equally arbitrarily, undefined procedures were given a rating of 0.5. Procedures which gave biased samples were (also arbitrarily) given a rating of 0.75 if the bias was known and defined. Procedures which gave double-biased samples were given a rating of 0.9 (if the biases are known and defined). The ratings of the various sampling plans are summarized in Table 1.1-1.

Table 1.1-1. Sampling Procedure Rating

Sampling Procedure	Confidence
Random Sample	1.0
Double Biased Sample	0.9
Single Biased Sample	0.75
Undefined	0.5

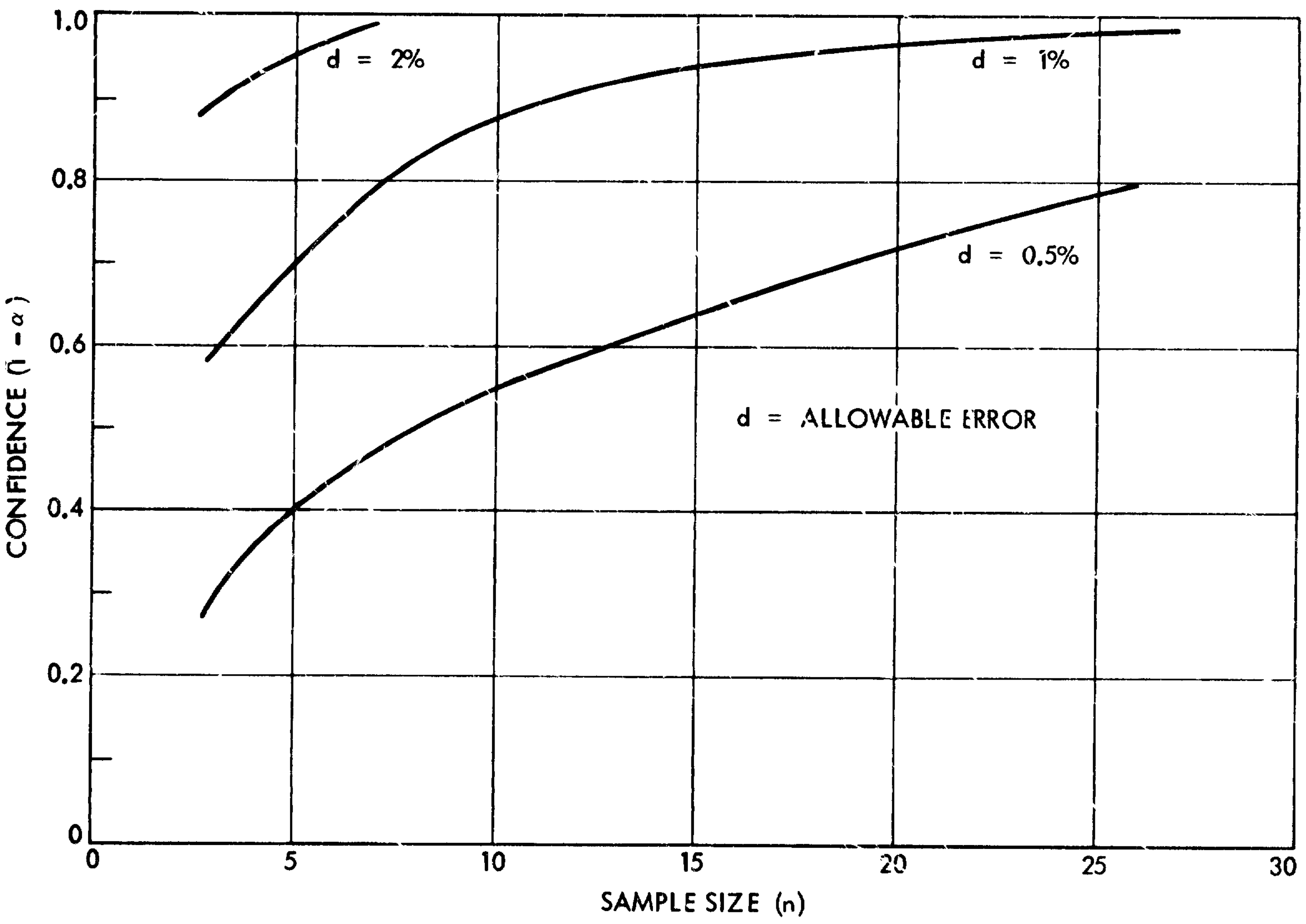


Figure 1.1-1. Confidence in Test Data as a Function of Sample Size with Allowable Error as a Parameter

"Sample bias" is an indicator that a sample does not "truly" represent the population from which it was selected. For example, let it be desired to evaluate by test certain characteristics of solar cells that are contained in the output distribution given above in the "Sample Size" discussion, and let it be stipulated that the maximum sample size shall be seven cells. There are essentially four different ways in which so-called random samples can be chosen to represent the "average" characteristics:

a) "Haphazardly" without regard to the electrical groupings

b) One cell out of each electrical group

c) All cells from Group No. 4 (i.e., from the "average" group)

d) Cells from as many groups as possible, selected such that the mean and the standard deviation of the sample are as nearly as possible the same as those of the population. (One solution: one cell each from Group Nos. 3, 6 and 7, and two cells each from Group Nos. 4 and 5.)

While it is clear that none of these sampling plans can result in a true "random" sample of such limited size that represents the entire population satisfactorily, it reflects a typical, real-life situation. With regard to the establishment of quality criteria, sampling plan (a) is called "undefined", Plans (b) and (c) are "biased" and Plan (d) is defined as a "random sample." A double biased sample is selected by a double sampling plan composed of two biased samplings.

The reason for rating double-biased samples lower than random samples was that even though the double-biased samples may be selected such that their mean is extremely representative of the population m, the double-biased sample mean is the average value of cells with mean performance (at 1 AU, 28°C) rather than the average value of random cells.

1.1.3 Sample Manufacturing Date

Current state of the art n-on-p silicon solar cells were developed prior to 1964 and first available in production lots in 1964. Therefore, n-on-p cell test data obtained prior to 1964 is considered experimental and, therefore, not acceptable for inclusion in this handbook, except for historical review purposes.

1.1.4 Illumination Source and Spectrum

This criterion was evaluated with respect to a go no-go-standard. Data from tungsten sources were not used in the handbook except for historical purposes. Natural sunlight and high quality Xenon solar simulators (or equivalent) were the only acceptable illumination sources. With respect to the spectral content of sources, AM0 is acceptable for simulators, while either AM0 or AM1 are acceptable for natural sunlight. AM0

sunlight data have inherent errors associated with telemetry while AM1 sunlight data have inherent errors associated with conversion to equivalent AM0 data. Even high quality data from simulators have inherent intensity, uniformity, and stability errors. The inherent errors for the three acceptable source-spectra combinations above were considered to be approximately equal in magnitude (±2 percent) for conventional solar cells. Consequently, this criteria was not graded; rather, it was either acceptable or unacceptable. (See Table 1.1-2.) The recently developed highly blue-sensitive cells were treated separately on an individual basis.

Table 1.1-2. Type of Source and Spectrum Criteria

Source	AM0	AM1
Xenon (or equivalent) Simulator	Acceptable	Unacceptable
Natural Sunlight	Acceptable	Acceptable
Tungsten	Unacceptable	Unacceptable
Other	Unacceptable	Unacceptable

1.1.5 Intensity Stability

Intensity stability has a definite and measurable effect on solar cell output. Any given percentage variation in intensity causes an approximately equal percentage error in solar cell current and power output. Consequently, the confidence value given for the intensity stability criterion is equal to 1 minus the percentage variation in intensity, as shown in Figure 1.1-2. Typically, the intensity variation is ±1 percent, corresponding to a confidence of 0.9[illegible].

1.1.6 Intensity Uniformity

Variation in intensity uniformity has a similar effect on solar cell output as intensity instability. Any percentage variation in uniformity can cause an approximately equal percentage error in solar cell measurements. Consequently, the confidence value given for the intensity uniformity criterion is equal to 1 minus the maximum percentage variation in intensity uniformity as shown in Figure 1.1-3. A typical intensity uniformity is ±1 percent so that the maximum variation is 2 percent, corresponding to an intensity uniformity of 0.98. Note that maximum variation is used rather than variation from an average intensity since it is not always possible to calibrate the light source at a point representing the average intensity in the test plane.

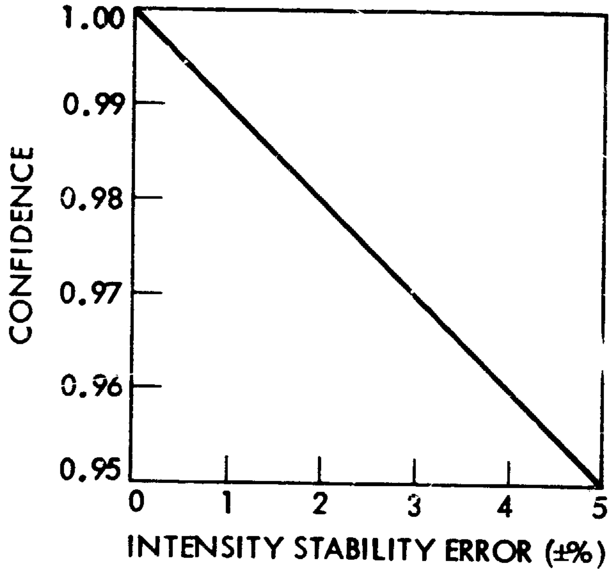


Figure 1.1-2. Confidence Factors for Intensity Stability Errors

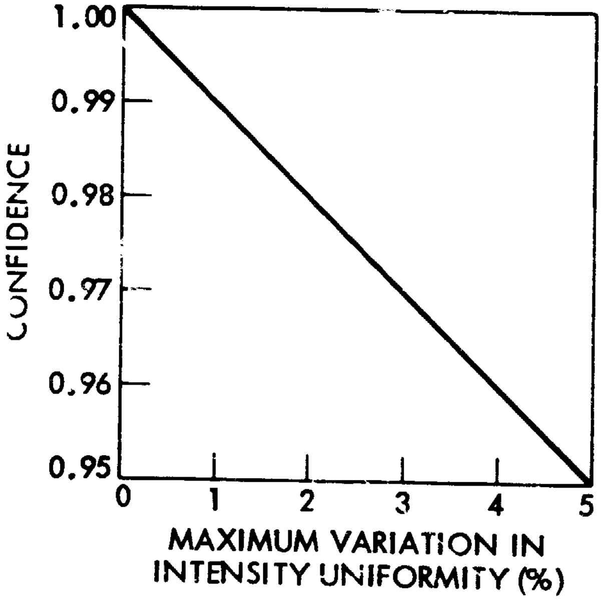


Figure 1.1-3. Confidence Factors for Intensity Uniformity Errors

1.1.7 Solar Simulator Calibration Technique

The use of a "working" standard cell for light source calibration can diminish the systematic test error caused by imperfect simulation of the AM0 solar spectrum if (a) the standard cell spectrally represents the population, and (b) the standard cell has been calibrated either in natural AM0 sunlight or in an AM0 simulator against a spectrally similar. "primary" standard solar cell. Other calibration procedures than these may lead to unknown test errors.

The total solar cell output measurement error which can be caused by improper working standard cell selection and calibration was estimated to be between 0 and 5 percent. The 5 percent error limit was based on a computer prediction for the case where a high-efficiency n-on-p violet-sensitive solar cell is tested with a blue-deficient X-25 solar simulator which was calibrated with a standard n-on-p solar cell. Again, the estimated potential error was expressed as a risk, with the percent error equal to the percent risk. Table 1.1-3 reflects errors of various standard solar cells. A primary standard is defined as one that has actually been calibrated during a balloon flight. A secondary standard has been calibrated on the ground against a primary, and a tertiary has been calibrated against a secondary. A working standard is one which is used to calibrate the light source, it may be a primary, secondary, or lower level standard cell.

Table 1.1-3. Confidence Factors for Standard Solar Cells Used for Light Source Calibration

<table>
<tr><th>Working Standard</th><th colspan="8">Standard Cell Spectrally Represents Population</th></tr>
<tr><td>Primary</td><td colspan="4">Yes
1.00</td><td colspan="4">No
0.99</td></tr>
<tr><td>Secondary</td><td colspan="2">Yes
0.99</td><td colspan="2">No
0.98</td><td colspan="2">Yes
0.98</td><td colspan="2">No
0.97</td></tr>
<tr><td>Tertiary</td><td>Yes
0.98</td><td>No
0.97</td><td>Yes
0.97</td><td>No
0.96</td><td>Yes
0.97</td><td>No
0.96</td><td>Yes
0.96</td><td>No
0.95</td></tr>
</table>

If more than one standard cell is used to calibrate a particular light level using the average output of the standards, the confidence factor C may be increased to $C^{1/n}$ where n is the number of standard cells used.

Thermocouples, IR-sensors, or other radiation measuring devices are not acceptable for solar simulator intensity calibration, except that they may be used to determine the relative (not absolute) spectral content of the simulator.

1.1.8 Calibration Frequency

The confidence factors of Table 1.1-3 were predicated on annual recalibration of the standards and 30-minute intervals between solar simulator recalibration or check. For less frequent calibration, multiply the confidence factors of Table 1.1-3 with the factors of Table 1.1-4.

1.1.9 Temperature Control

Inadequate solar cell temperature control or uncertainty in the actual cell temperature may influence the accuracy of the measured parameters. For simplicity, it was assumed that the approximation of 0.5 percent power change per degree Celsius temperature change holds for all other parameters and relates directly to the confidence in the test data, as shown in Figure 1.1-4. The temperature uncertainty was to be estimated from the applicable test report.

1.1.10 Voltage Pickoff

Cells tested with four-point contacts or wires soldered to the cells were rated at 1.0. All other, nonstandard contacting methods were rated 0.75.

Table 1.1-4. Confidence Reduction Factors for Calibration Frequency

Item To Be Calibrated	Time Since Last Calibration				
	0 to 1 year	1 to 2 years	2 to 3 years	3 to 5 years	over 5 years
Primary Standard	1.00	1.00	0.99	0.99	0.98
Secondary Standard	1.00	1.00	0.99	0.99	0.97
Tertiary Standard	1.00	0.99	0.99	0.98	0.96
Working Standard*	0 - 3 mo	3 - 6 mo	6 - 12 mo	1 - 3 yr	3 yr
	1.00	0.95	0.90	0.80	0.50
Solar Simulator	0 - 30 min	30 - 60 min	1 - 2 h	2 - 4 h	4 h
	1.00	0.99	0.98	0.96	0.90

*If primary, secondary, or tertiary standard solar cells are used as a day-to-day working standard, their confidence factors shall be reduced to the factors for working standards.

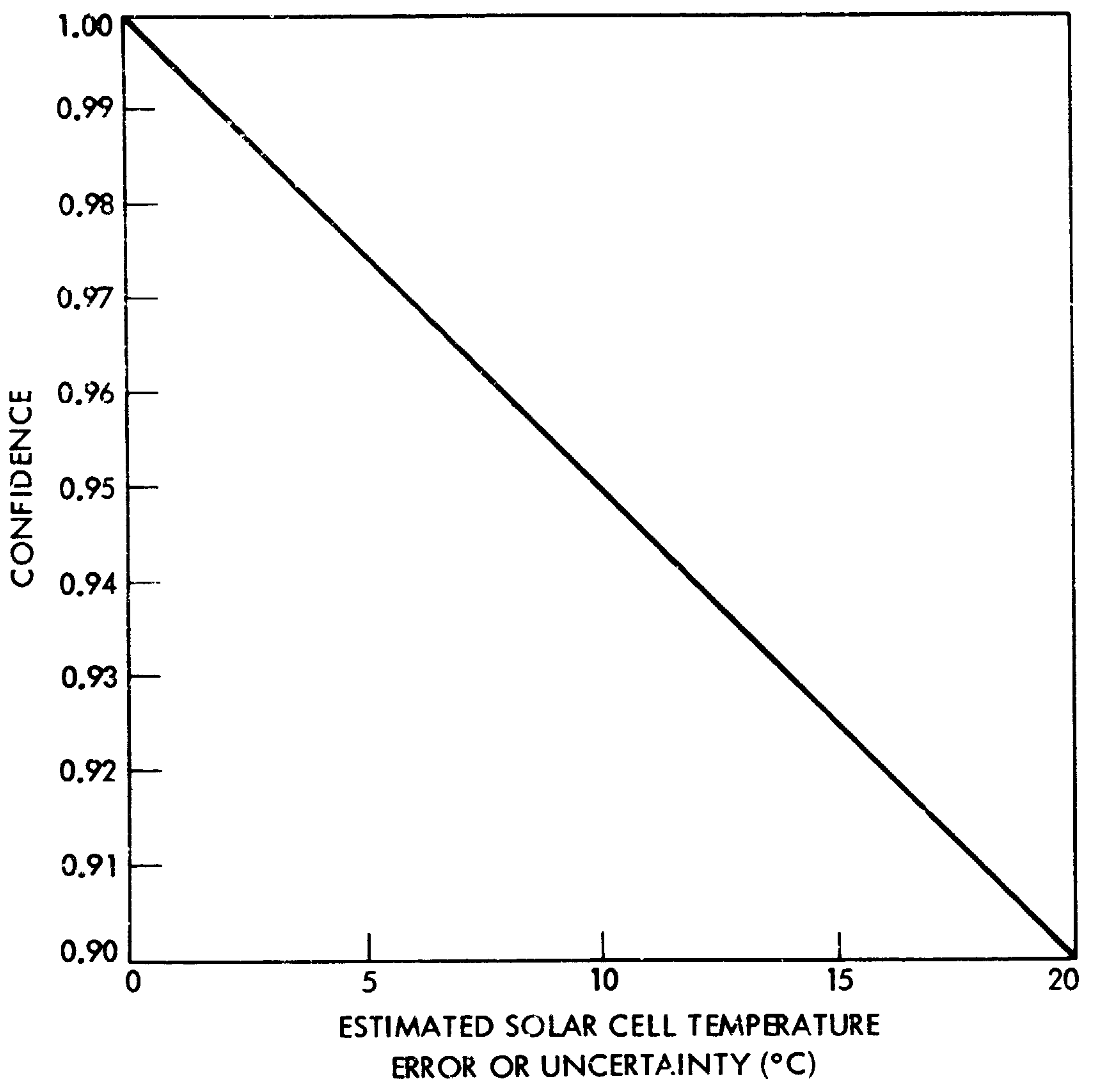


Figure 1.1-4. Confidence Factors for Cell Temperature Control

1.1.11 Test Instrumentation

Solar cell measuring equipment and test setups were rated 1.00 if they conformed to generally acceptable practices. Unusual equipment and setups were rated between 0.75 and 0.90, depending on how much confidence could be gained from the applicable test report.

HANDBOOK DATA QUALITY RATING

Cell Manufacturer: ____________________

Cell Size: ____________________

Cell Thickness: ____________________

Contact and Grid: ____________________

Base Resistivity: ____________________

AR Coating: ____________________

Cover: ____________________

Data Identification: ____________________

Intensity Range: ____________________

Temperature Range: ____________________

Measured Parameter: ____________________

Spectral Response: ____________________

Other features: ____________________

	Rating
Manufacturing Date: ____________________	
Sample Size: ____________________	
Sampling Procedure: ____________________	
____________________	
Type of Source and Spectrum: ____________________	
Intensity Stability: ____________________	
Intensity Uniformity: ____________________	
Standard Solar Cell Calibration Frequency: ____________________	
Temperature Control: ____________________	
Voltage-Pickoff: ____________________	
Instrumentation: ____________________	
Overall Total: ____________________	

Summary Test Results:

	P_{max}	V_{mp}	V_{oc}	I_{mp}	I_{sc}
Average Output:					
Sample Variance:					

Deviation from Expected Results: ____________________

Other Comments: ____________________

____

Figure 1.1-5. Example of Data Quality Rating Sheet

1.2 SOLAR CELL DATA PROBLEMS

1.2.1 Results of Data Evaluation

Application of the data quality criteria to various sets of test data which were collected for possible inclusion in the handbook resulted in two distinctly different groups of data: "high quality" and "unacceptable" data. Different quality ratings were derived by completing forms, as shown in Figure 1.1-5. A study and review of these filled-in forms, however, revealed that small differences in quality ratings between different sets of "high quality" data were most likely due to limitations of the rating scales applied rather than to variations in the quality of the data. "Unacceptable" data were primarily obtained under tungsten light sources or under uncontrolled test conditions. The following conclusions were drawn from these data quality analyses:

- **To be of practical use and to convey confidence in the results, published test data should state (as a minimum) all of the test and calibration conditions which are shown in Figure 1.1-5.**

- **The test results published on relatively small sample sizes (such as five-cell samples for radiation testing, for example) may be quite acceptable (see Figure 1.1-1).**

1.2.2 Solar Cell Test Data

One of the major efforts during a typical spacecraft-oriented solar array design process is concerned with "choosing" the "right" solar cell and coverglass for a specific mission. The word "choosing" is used here to signal a general lack of sets of self-consistent and cohesive solar cell test data which would readily permit orderly tradeoff or design optimization studies to be conducted. The test data which one actually finds is often representative of a small sample with a relatively narrow statistical spread, taken from a production population with a relatively large statistical spread. Some examples of such biased test sample groups are very high efficiency cells obtained as "evaluation samples" from hopeful vendors, or "bottom of the barrel" samples left over from earlier contracts. Most solar cell test programs have indeed been executed with reasonable care, and often statistical treatment of the data indicates that the data is indeed statistically valid at high confidence. The problem shows up later, however, when data is being cross plotted. For instance, even in "reputable" data such interesting phenomena have appeared as the averaged maximum power current being equal to or higher than the averaged short-circuit current; or the averaged 25°C, AM0 maximum power of 10 ohm-cm cells being equal to or higher than the 2 ohm-cm cell output for the same cell thickness rather than being lower. What obviously has happened is that in the first case, nondiscriminating averaging biased the reduced data, while in the second case, the 10 ohm-cm test samples were taken from the upper end of the production spread and the 2 ohm-cm samples from the lower end.

Unfortunately, it has not been possible to examine the sets of solar cell data included in this handbook, either for being self-consistent within a given set, or for consistency between different sets of data. The user of the solar cell data presented herein should bear in mind that the data - while it is the "best" data available - may be misleading when used without scrutiny in tradeoff studies.

1.2.3 Material Test Data

Data quality criteria for other than solar cell characteristics are currently unknown. Test procedures, test methods, and test specimens are frequently insufficiently described in the literature to permit even experts in the respective fields to draw significant conclusions regarding the validity of the information presented. Often, the experimental results reported by different investigators differ widely, but no means were found to reconcile or otherwise explain these differences. Therefore, the solar cell array designer is cautioned (when using the data presented in this handbook) against drawing conclusions that may not be warranted due to inherent limitations of the data.

CHAPTER 3

SOLAR CELLS

CONTENTS

CHAPTER 3

SOLAR CELLS

3.1 COMPARATIVE PERFORMANCE OF DIFFERENT SOLAR CELL TYPES
SOLAR CELL TYPES

The data shown here is subject to change because the solar cell designs and their fabrication processes are continually being refined. (See the discussions in Sections 3.1 and 3.12 in Volume I.)

3.1.1 Performance of Different Families of Silicon Solar Cells (Ref. 3.1-1)

Cell Description

Cell Type: Various

Size: 2 x 2 cm

Thickness: 0.2 to 0.3 mm

Coatings: SiO (conventional) and Ta_2O_5 (field and hybrid)

Contacts: Conventional front and back contacts, Ti-Ag and Ti-Pd-Ag with and without solder

Gridlines: Three per cm (conventional), nine per cm (hybrid and field)

Junction Depth: 0.30 - 0.35 μm - conventional cell
0.15 - 0.20 μm - hybrid cell
0.18 - 0.23 μm - field cell

Manufacturer: Spectrolab

Back Surface Field: Conventional and hybrid cells without field; field cells with field.

Cover Glass: Fused silica, 0.15 mm thick, MgF coated, 0.35 μm cut-on blue-reflective filter for hybrid and field cells, 0.40 cut-on for conventional cells.

Test Conditions

Illumination: 1 solar constant AM0, X-25 solar simulator

Cell Temperature: 25°C

Data

3.1.2 Unirradiated Conventional Silicon Solar Cells of Different Thickness

Cell Description

Cell Type: Conventional

Size: 2 x 2 cm

Active Area: 3.8 and 3.9 cm^2

Base Resistivity: 2 and 10 ohm · cm

Coating: SiO

Contacts: Conventional front and back contacts, Ti-Ag with and without solder

Manufacturer: Centralab/OCLI, Heliotek/Spectrolab

Cover Glass: None

Test Conditions

Illumination: 1 solar constant AM0, X-25 solar simulator

Cell Temperature: 25° and 28°C

Data Analysis

All data represent averages of test samples (5 to 100 cells) normalized to 28°C cell temperature, 2 x 2 cm overall cell size

Data Results

Data results are shown in the following figures:

From Ref. 3.1-1. Reprinted with permission of the Deutsche Gesellschaft für Luft und Raumfahrt EV.

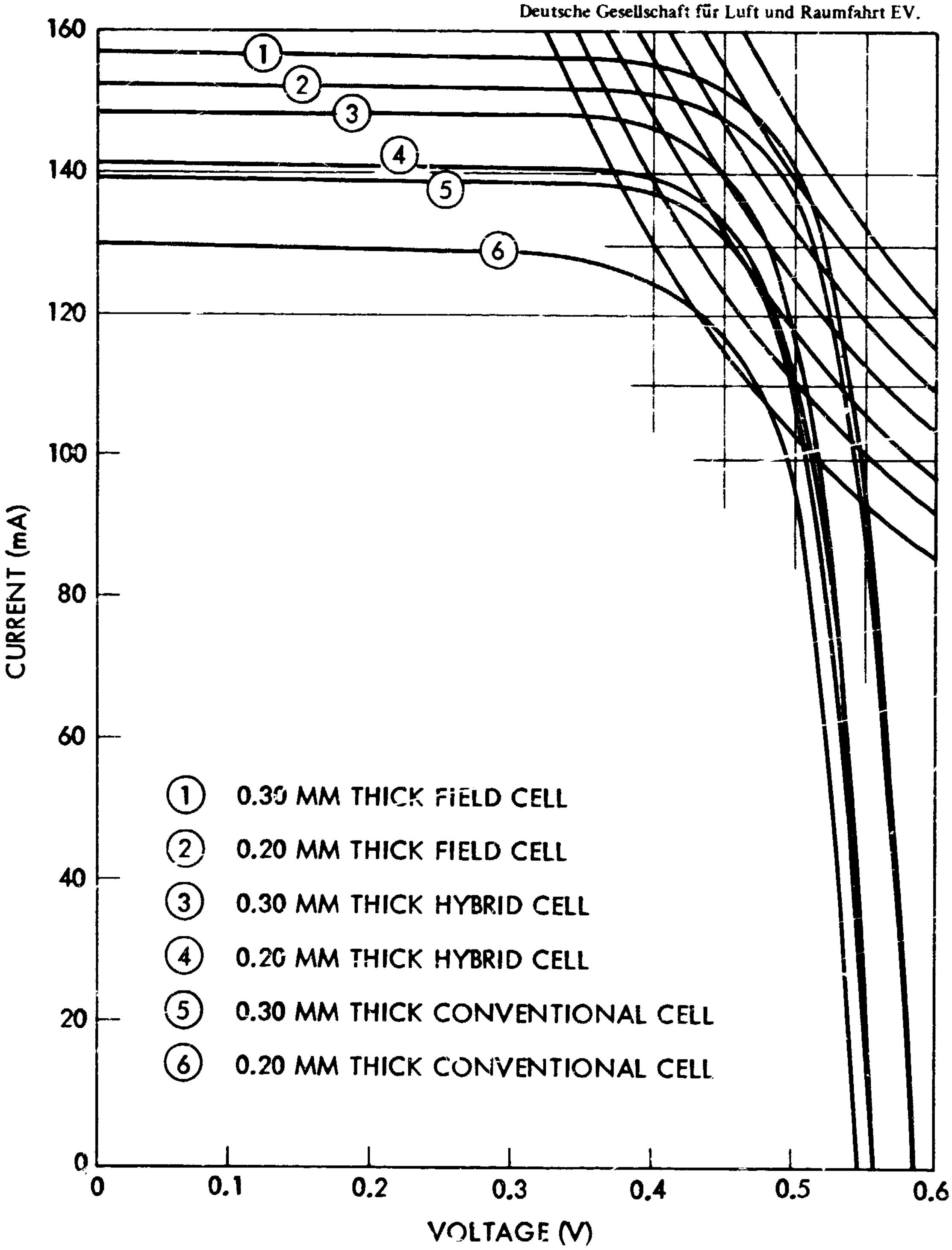


Figure 3.1-1. I-V Curves Showing Typical Output of Field, Hybrid, and Conventional Cells. (All cells of 10 ohm - cm base resistivity glassed, and tested at 25°C under one solar constant intensity of AM0 spectrum)

From Ref. 3.1-2. Reprinted with permission of the Deutsche Gesellschaft für Luft und Raumfahrt EV.

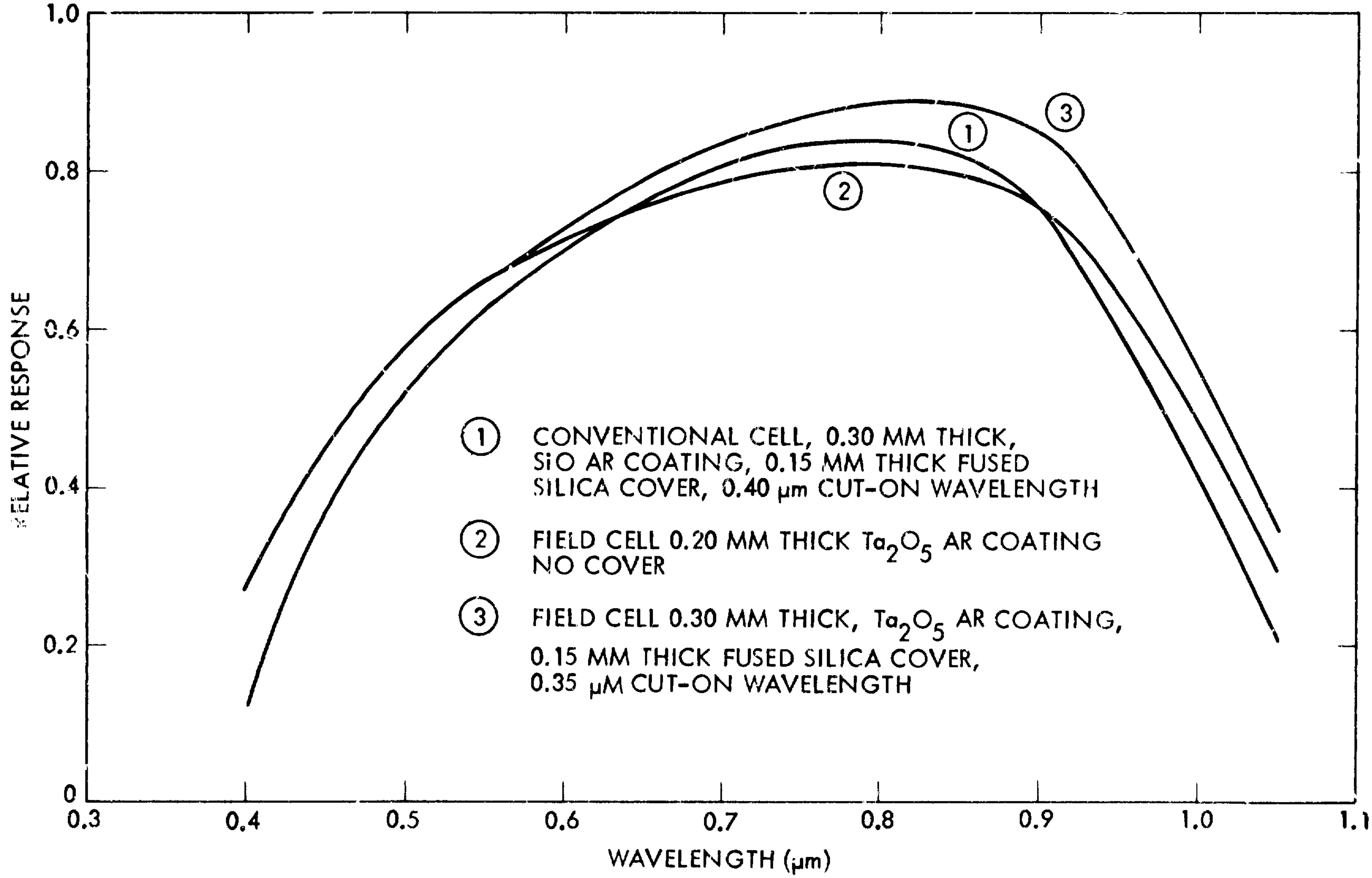


Figure 3.1-2. Spectral Response Curves of Field and Conventional Cells

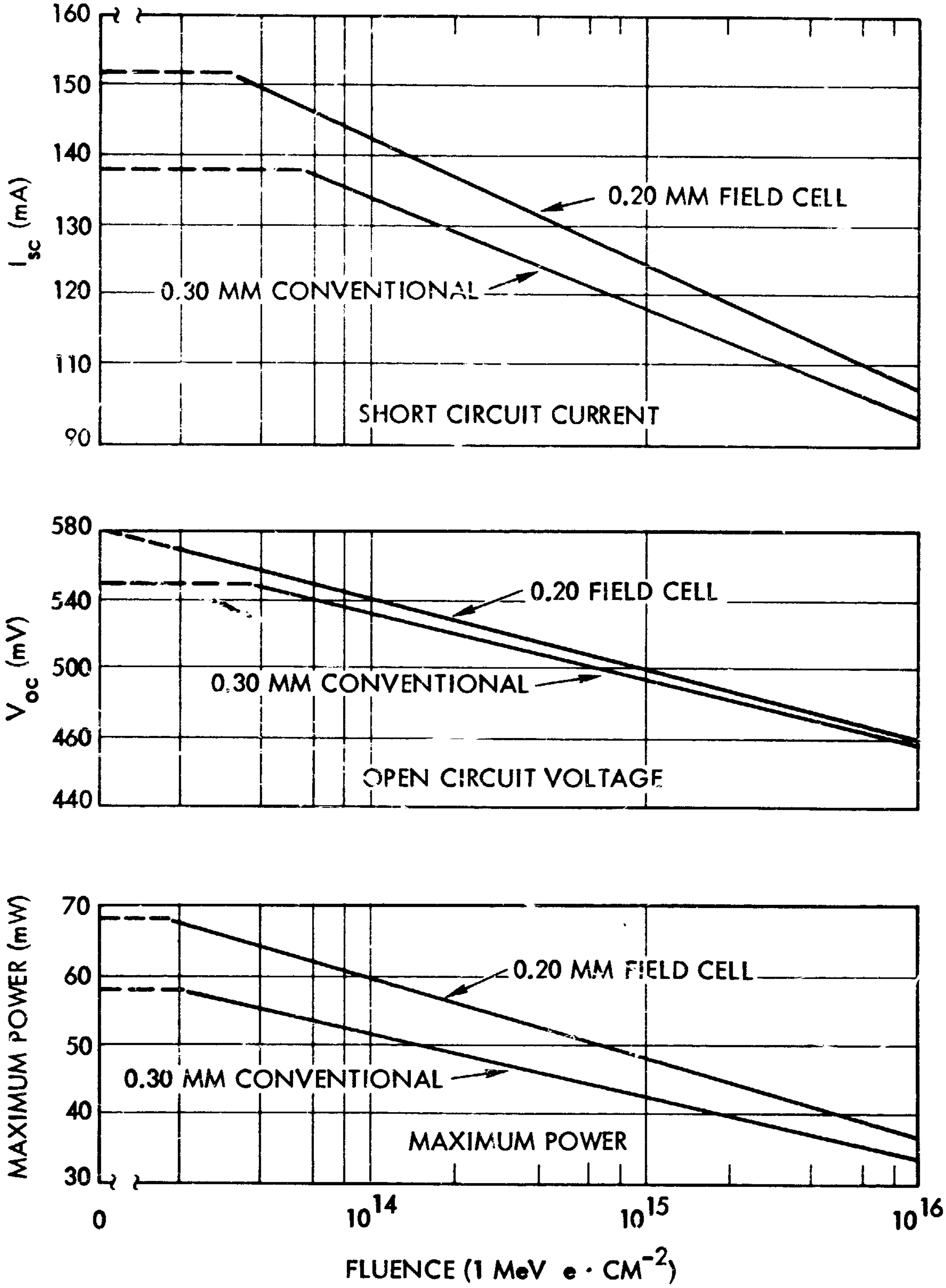


Figure 3.1-3. Effect of 1 MeV Electron Radiation on I_{sc}, V_{oc} and P_{max} for Glassed Field and Conventional 10-ohm · cm Cells

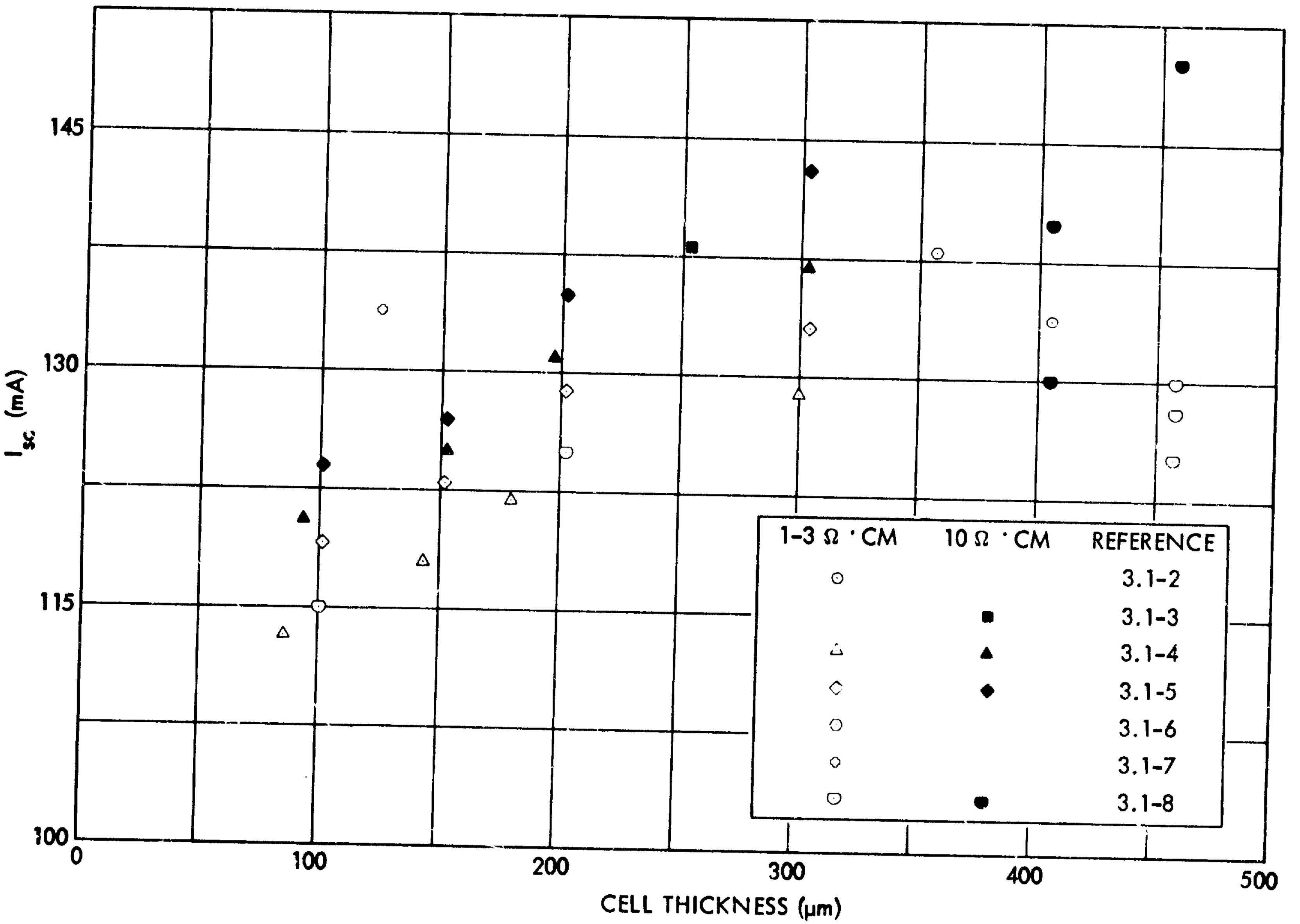


Figure 3.1-4. Short-Circuit Current Versus Cell Thickness

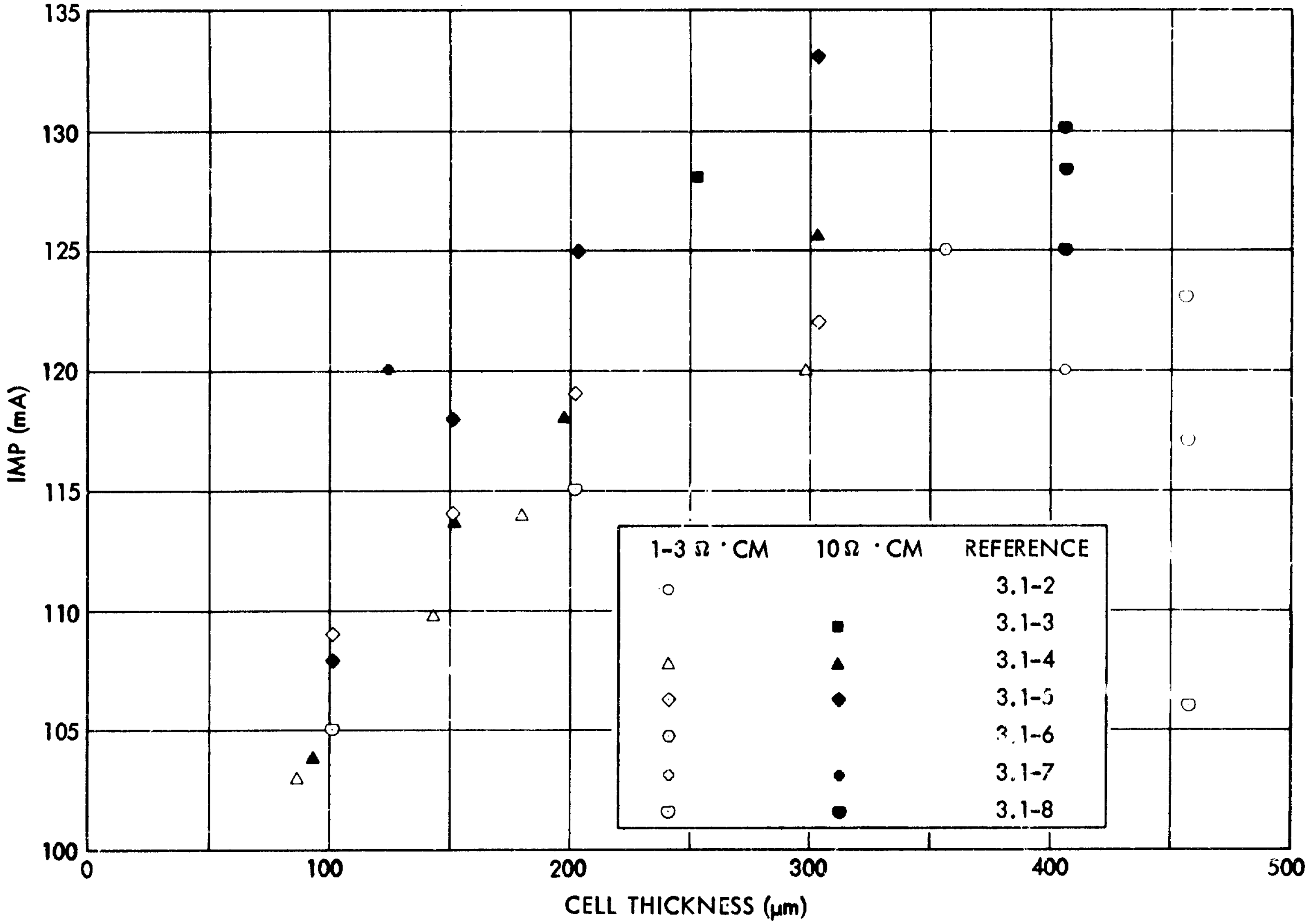


Figure 3.1-5. Maximum-Power Current Versus Cell Thickness

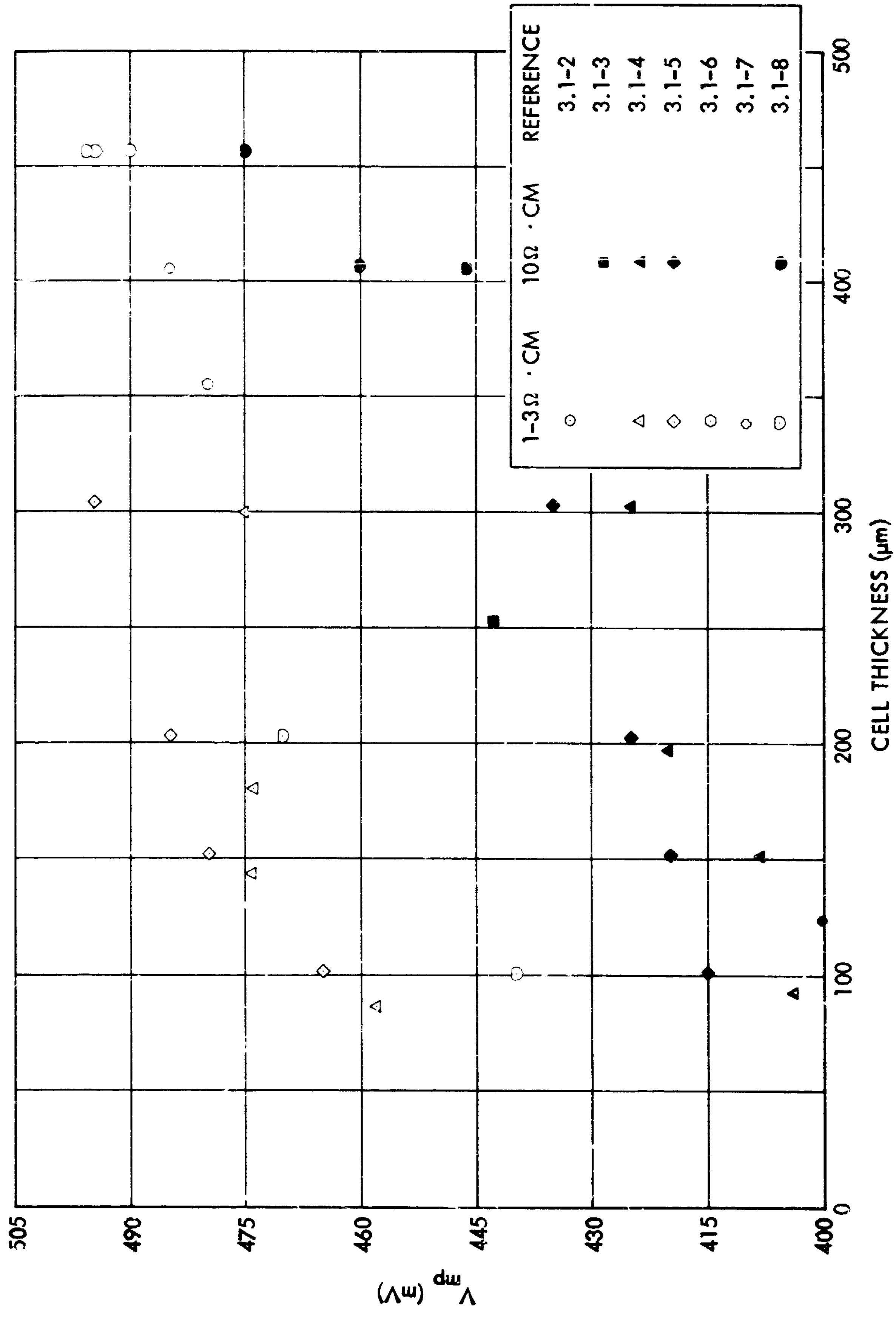


Figure 3.1-6. Maximum-Power Voltage Versus Cell Thickness

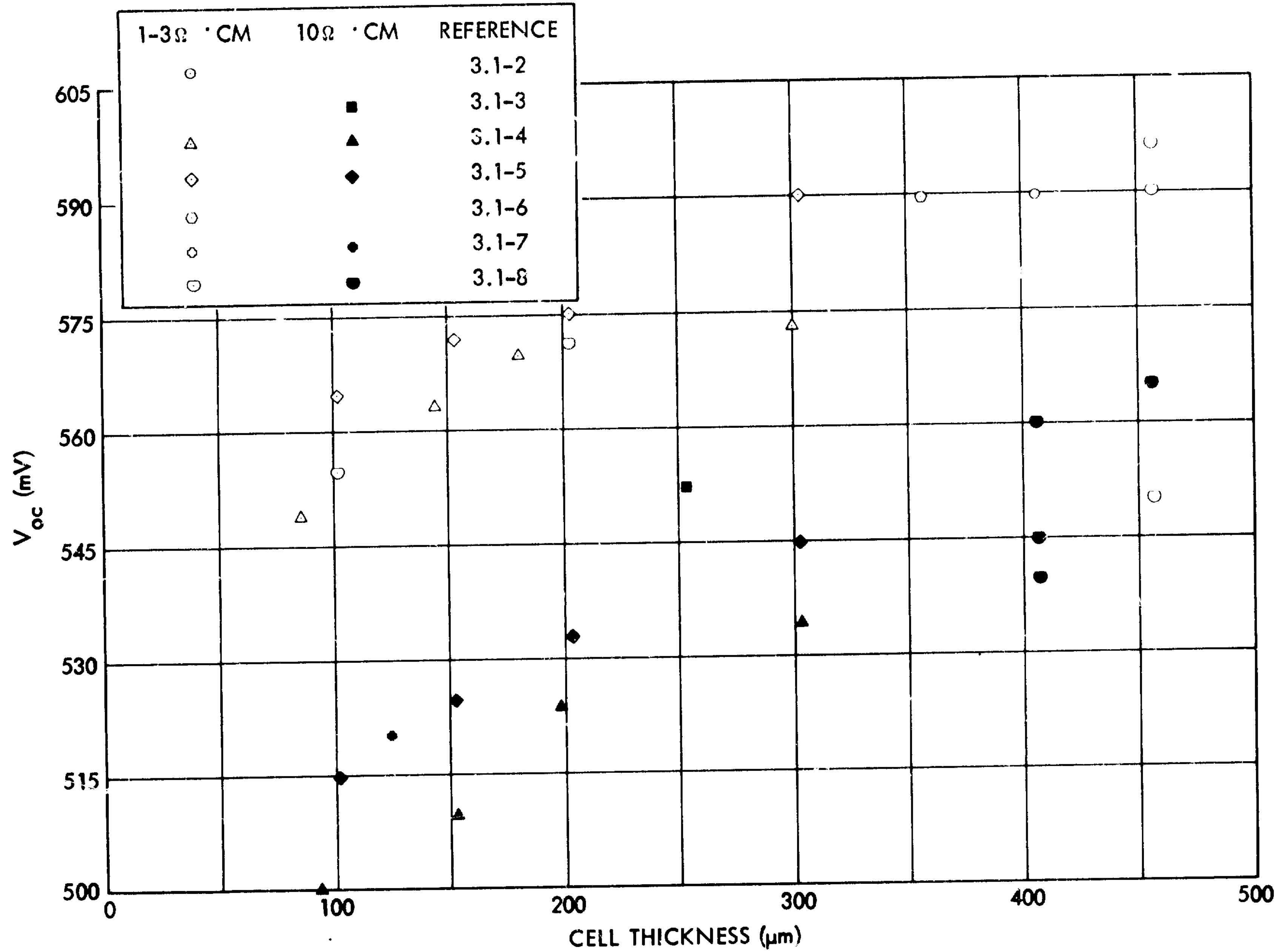


Figure 3.1-7. Open-Circuit Voltage Versus Cell Thickness

3.2 UNIRRADIATED SILICON SOLAR CELLS

3.2.1 I_{sc}, V_{oc}, I_{mp}, P_{mp} and Efficiency Versus Temperature and Intensity for Various Solar Cell Types (Ref. 3.2-1)

Cell Description

Glassed solar cells per Table 3.2-1.

Test Method and Equipment

Per Volume I, Section 11.2.

Experimental Results

Averaged data is shown in the following graphs and identified by "Test Plate" according to Table 3.2-1.

Table 3.2-1. Test Specimen Identification

JPL Test Plate	Solar Cell Description						
	Size (mm x mm x mm)	Base Resistivity (ohm·cm)	Polarity	Contact Type	AR Coating	Manu-facturer*	Manufac-turing Date (mo/year)
A	20 x 20 x 0.46	10	N/P	AgTi, Solder, Corner Dart	SiO	HK	2/69
B	20 x 20 x 0.46	2	N/P	AgPdTi, Solderless	SiO	HK	3/69
C	20 x 20 x 0.46	2	N/P	AgTi, Solder	[illegible]	HK	1/68
D	20 x 20 x 0.46	2	P/N	AgTi, Solder, Corner Dart	SiO	HK	6/69
E	20 x 20 x 0.46	2	N/P	AgPdTi, Solderless	SiO	CRL	4/69
F-1	20 x 20 x 0.46	10	N/P	AgTi, Solder, Wraparound	SiO	CRL	4/69
H	20 x 20 x 0.46	10	N/P	AgTi, Solder	SiO	CRL	11/69
J(a)	20 x 20 x 0.36	2	N/P	AgTi, Solder	SiO	HK	8/71
J(b)	20 x 20 x 0.36	2	N/P	AgTi, Solder	SiO	CRL	8/71
M	20 x 20 x 0.36	2	N/P	AgTi, Solder	TiOx	HK	5/73
N	20 x [illegible] x 0.30	2	N/P	AgPdTi, Solderless	SiO	CRL	11/74
O	20 x 20 x 0.30	10	N/P	AgPdTi, Solderless	Ta_2O_5	HK	2/75

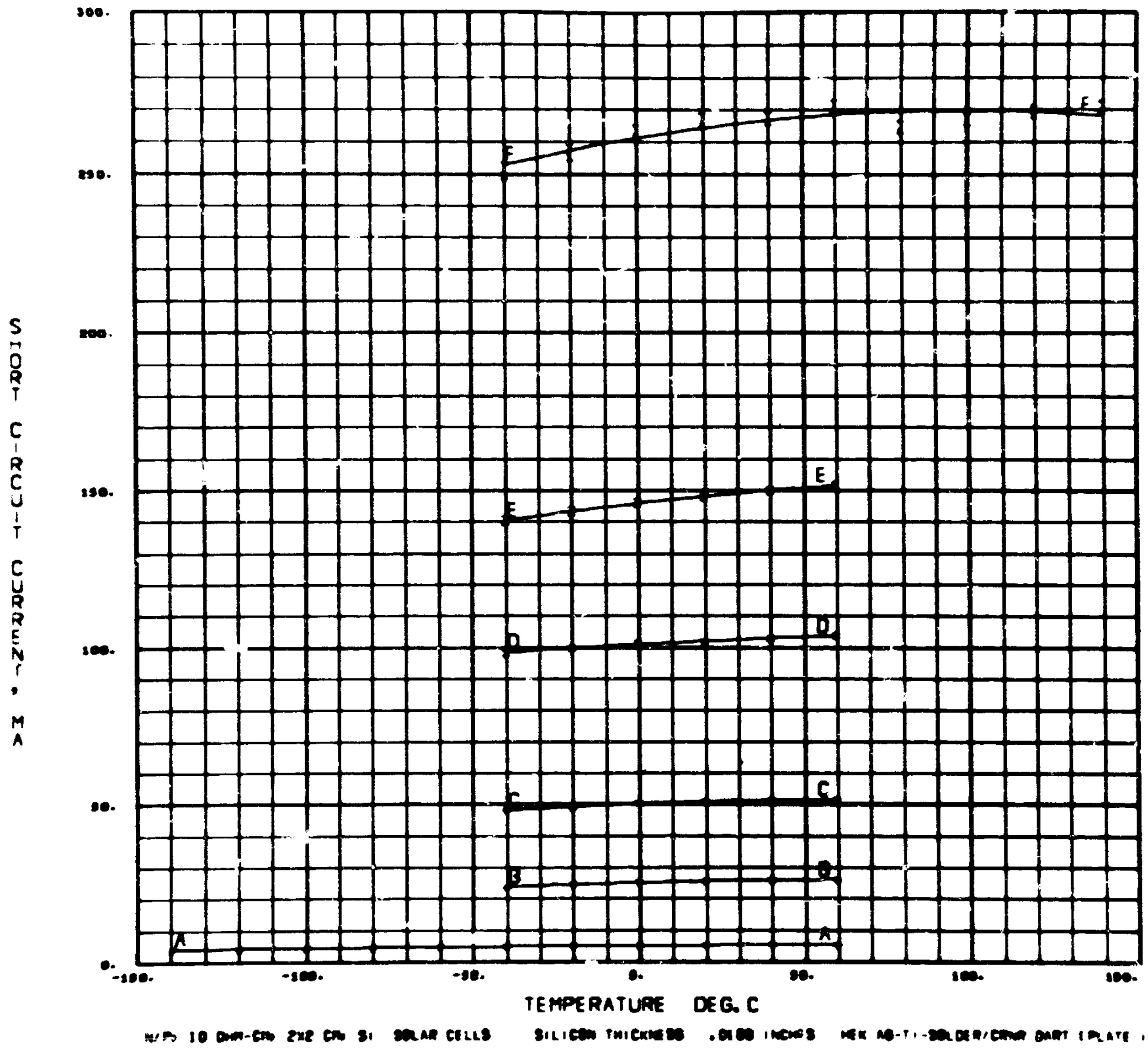
*HK = Heliotek, CRL = Centralab

Table 3.2-1. Test Specimen Identification (Continued)

Cover Description						Sampling Plan			
JPL Test Plate	Material*	Thick-ness (mm)	Cut-On Wave-length (nm)	AR Coating	Cover Adhesive	Popu-lation	Test Sample	JPL Plate Designator	Solar Cell Type
A	MS 0211	0.15	410	MgF	RTV-602	200	13	H-11	Conventional
B	MS 0211	0.15	410	MgF	RTV-602	100	13	H-16	Conventional
C	FS 7940	0.51	410	MgF	RTV-602	200	13	H-12(M71)	Conventional
D	MS 0211	0.15	410	MgF	RTV-602	100	13	H-17	Conventional
E	MS 0211	0.15	410	MgF	RTV-602	100	13	C-4	Conventional
F-1	MS 0211	0.15	410	MgF	RTV-602	250	13	C-2	Conventional
H	MS 0211	0.15	410	MgF	RTV-602	200	13	C-11	Conventional
J(a)	FS 7940	0.15	410	MgF	R63-489	600	7	H-37	Conventional
J(b)	FS 7940	0.15	410	MgF	R63-489	600	6	C-22	Conventional
M	FS 7940	0.15	410	MgF	R63-489	380	14	H-45	Conventional
N	FS7940	0.15	410	MgF	R63-489	100	14	C-42	High Efficiency
O	FS 7940	0.15	350	MgF	DC93-500	100	14	H-47	Helios

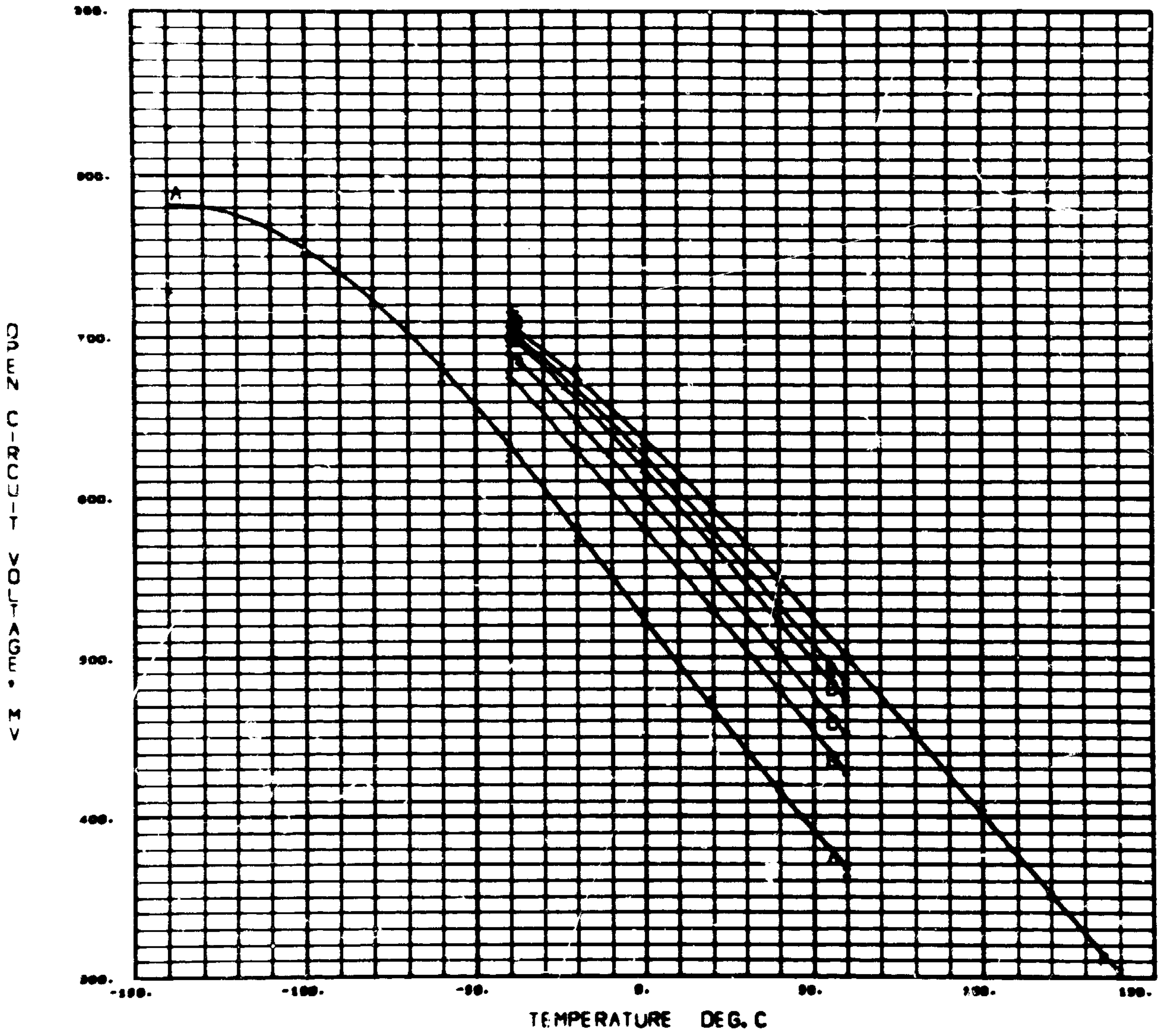
*MS = Microsheet, FS = Fused Silica

Plate A



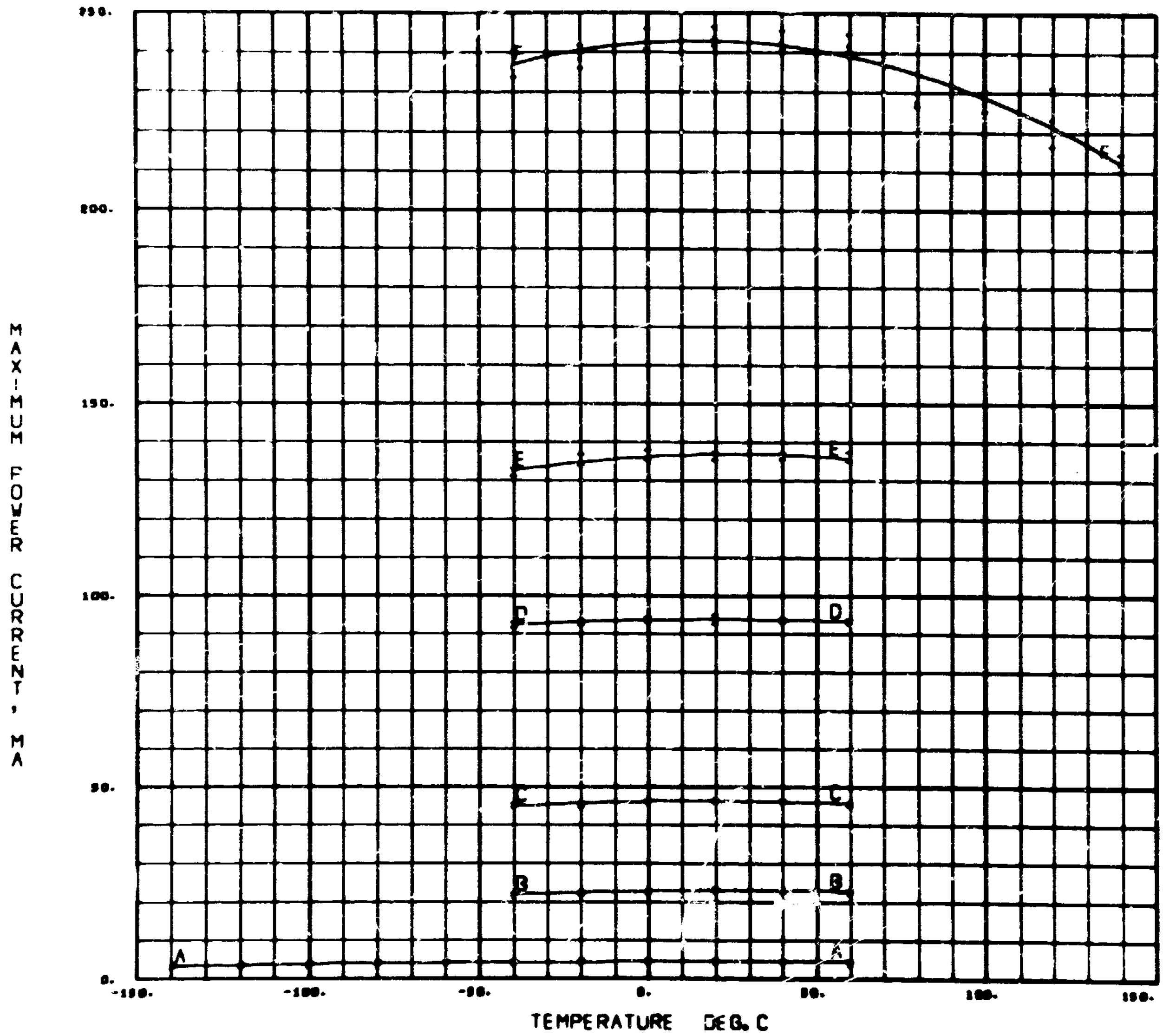
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate A



CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

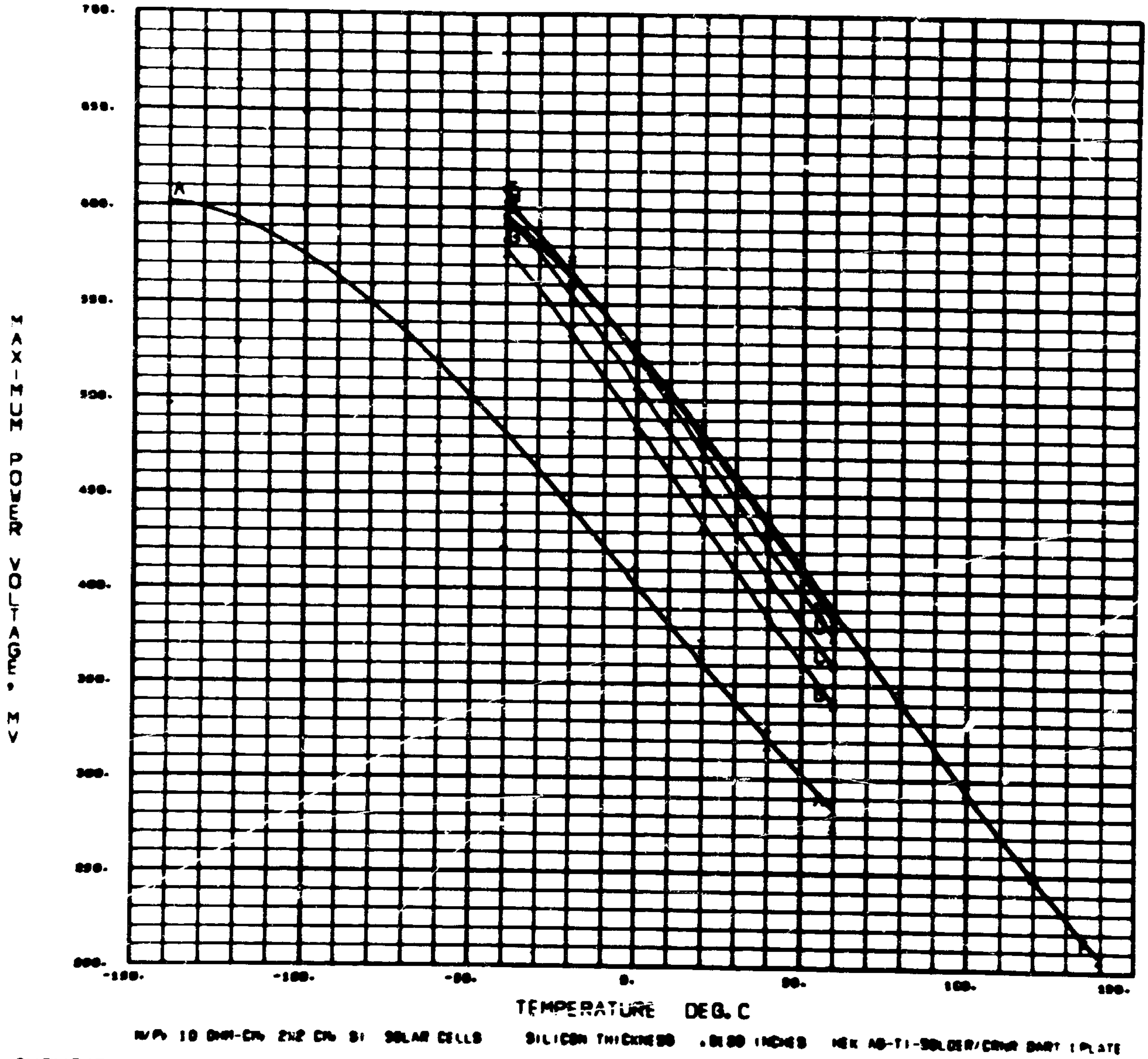
Plate A



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEX AG-TI-SOLDER/CRNR CART (PLATE)

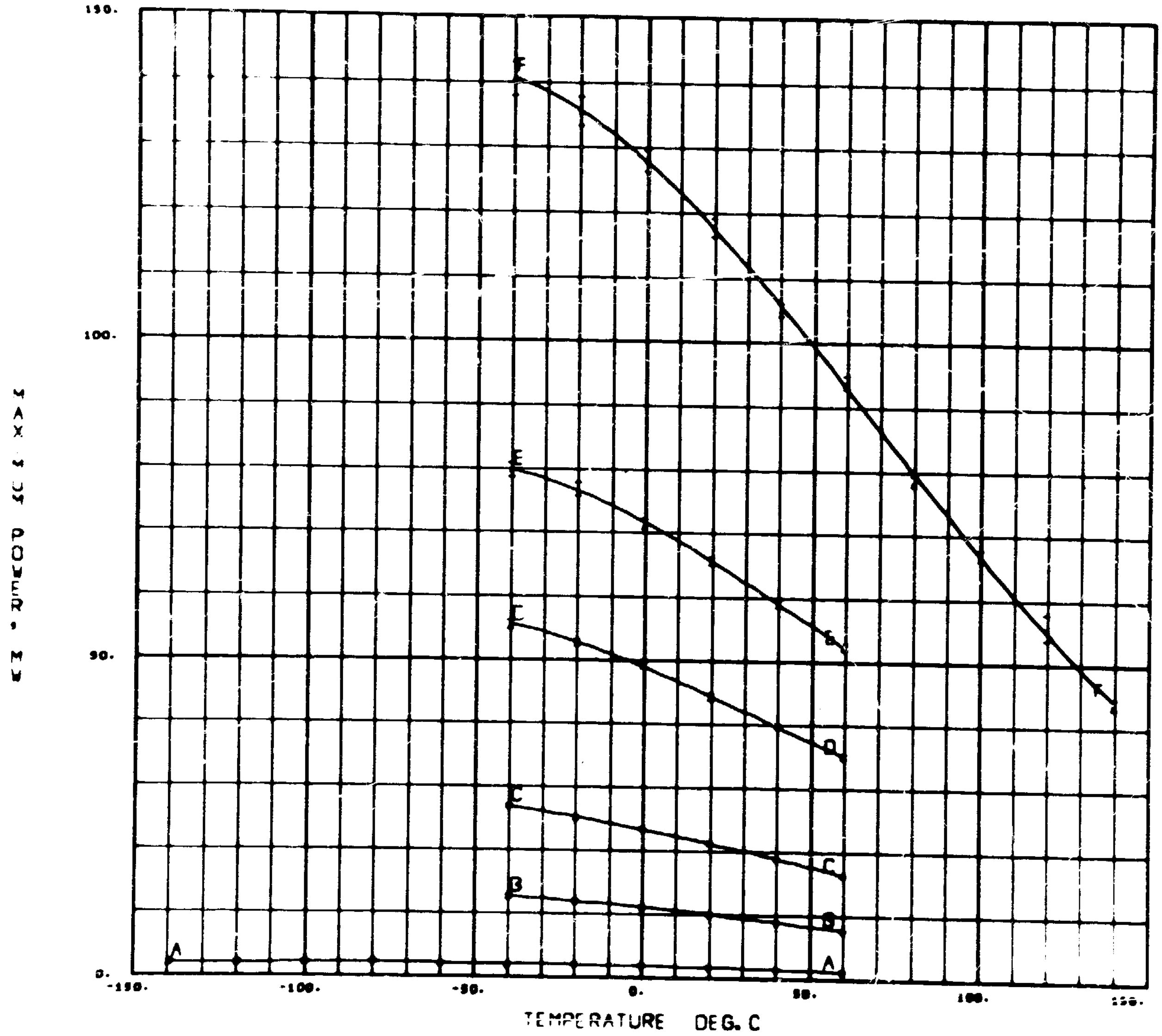
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate A



CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

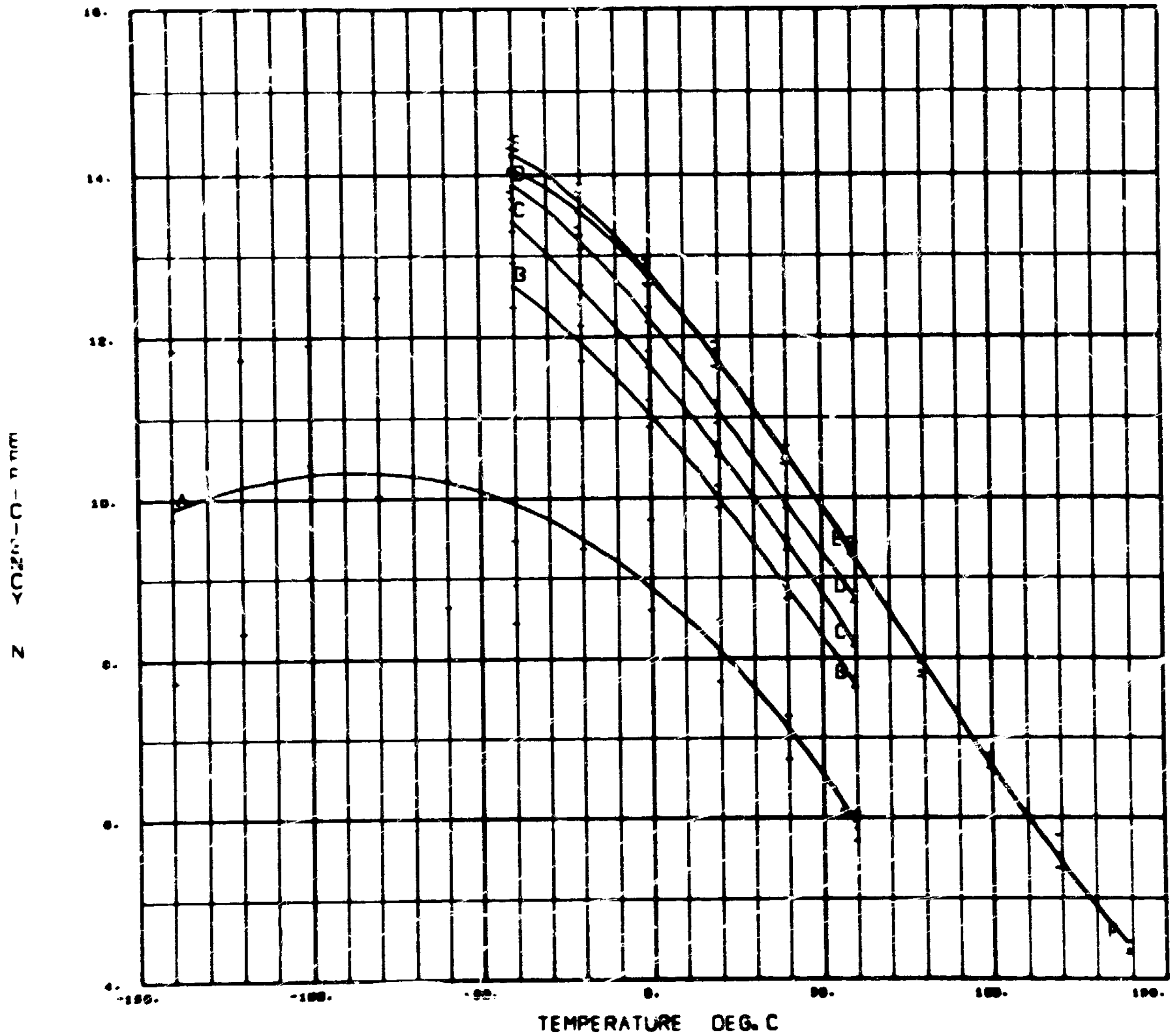
Plate A



N/P. 10 OHM-CM. 2X2 CM. SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AG-TI-SOLDER/CRNR DART PLATE

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

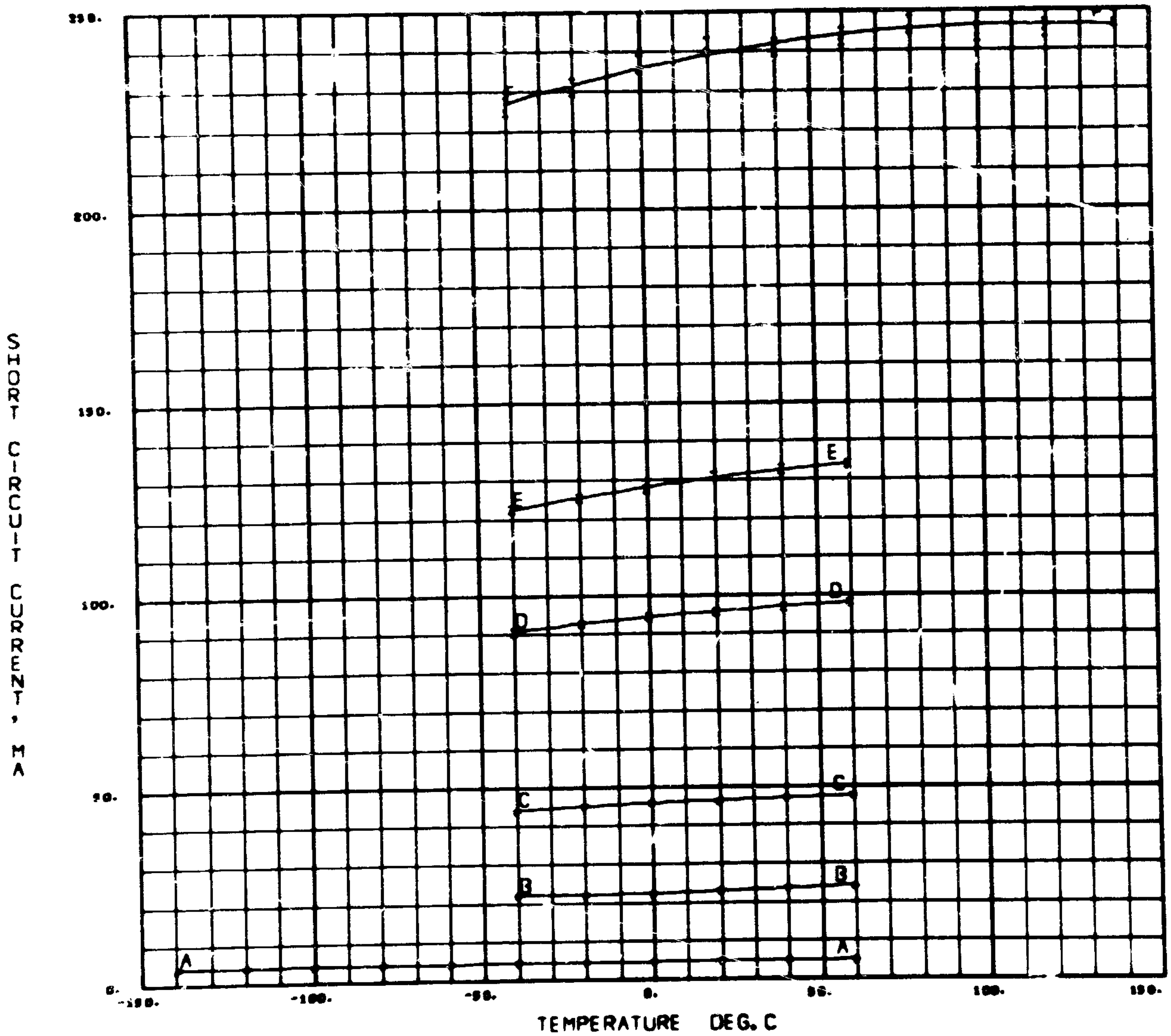
Plate A



N/P, 10 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEX AG-TI-SOLDER/CRNR DART (PLATE)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

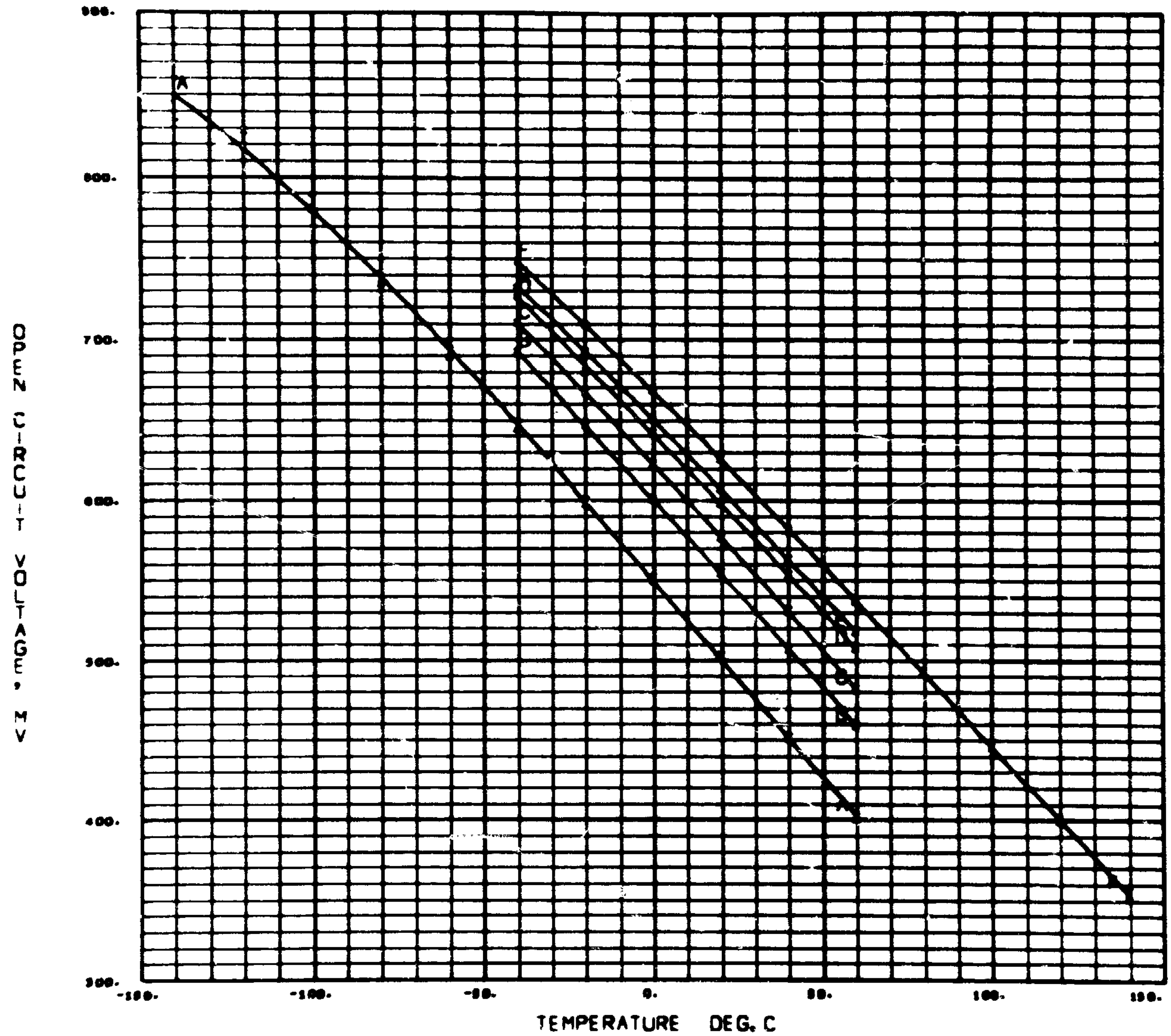
Plate B



N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AG-PD-TI-SOLDERLESS (PLATE B)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

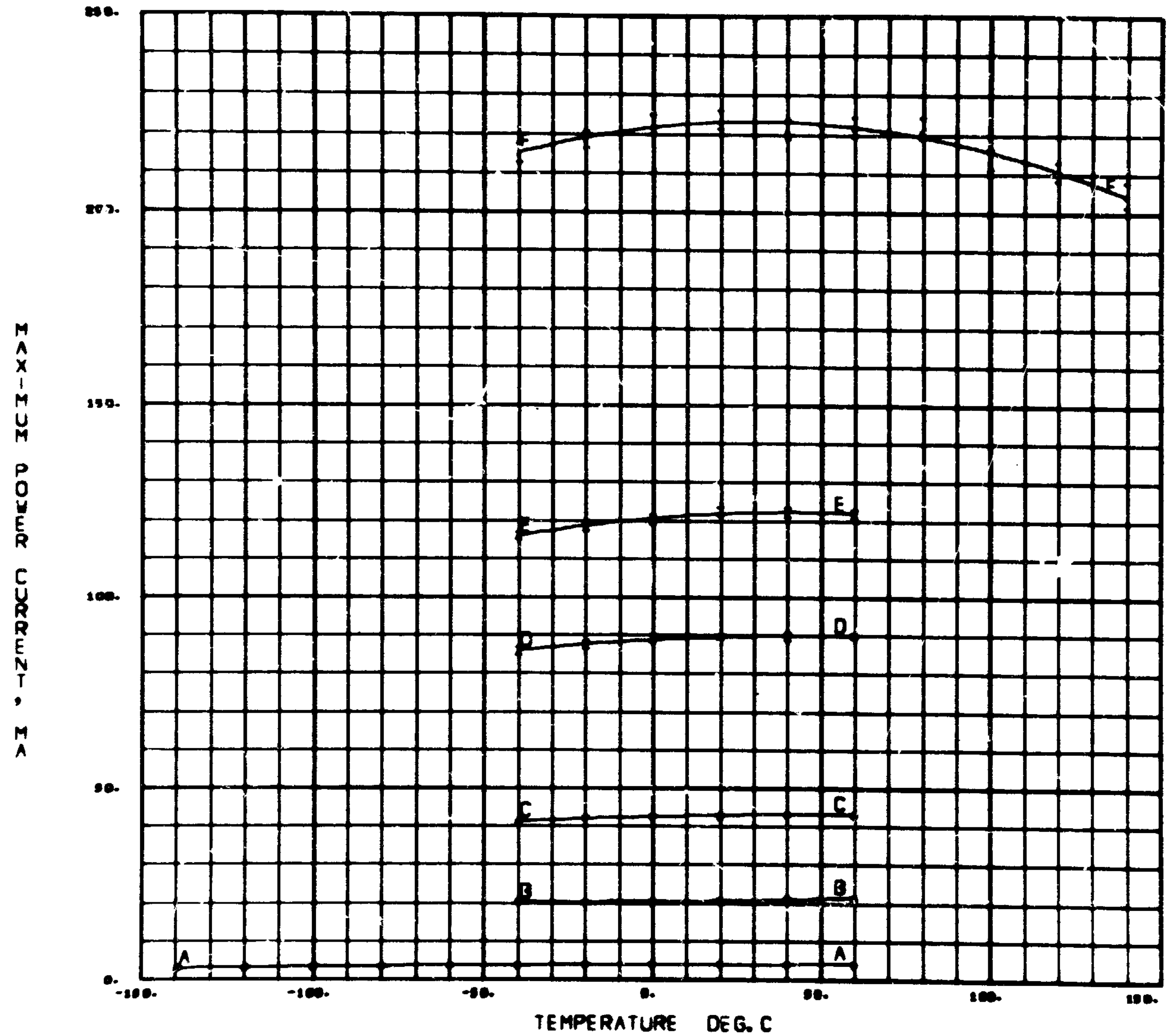
Plate B



N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AG-PD-TI-SOLDERLESS (PLATE B)

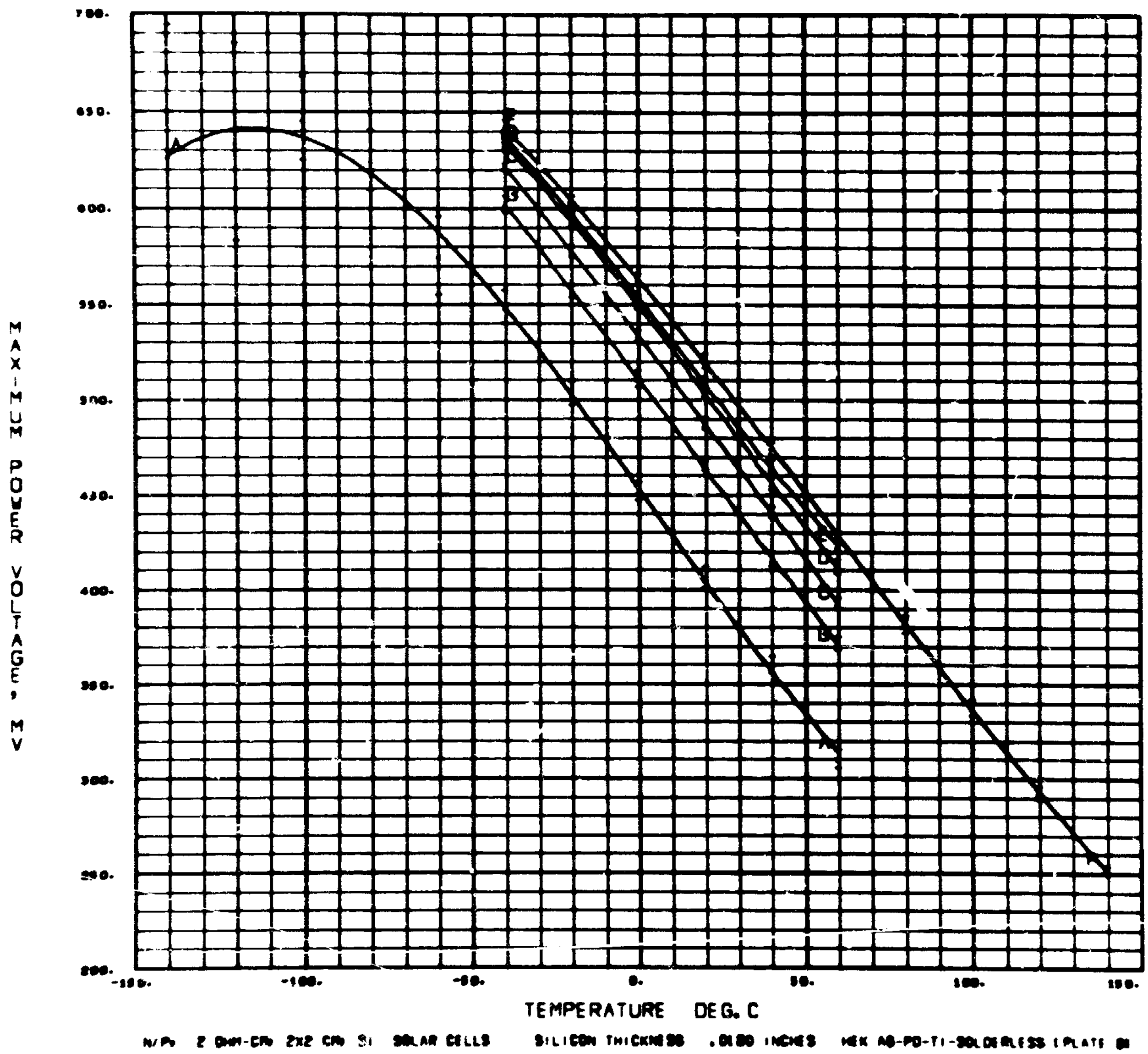
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate B



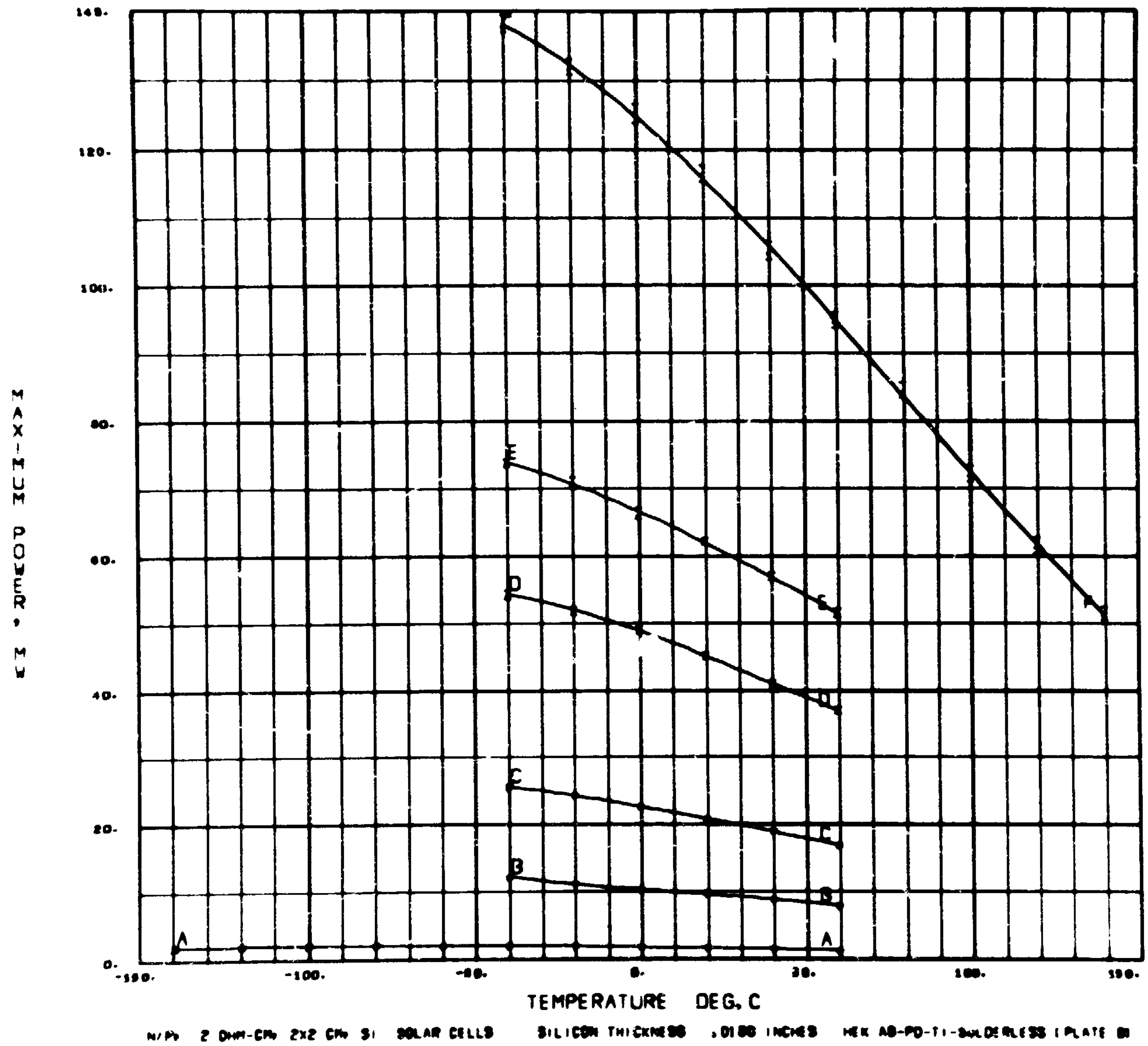
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate B



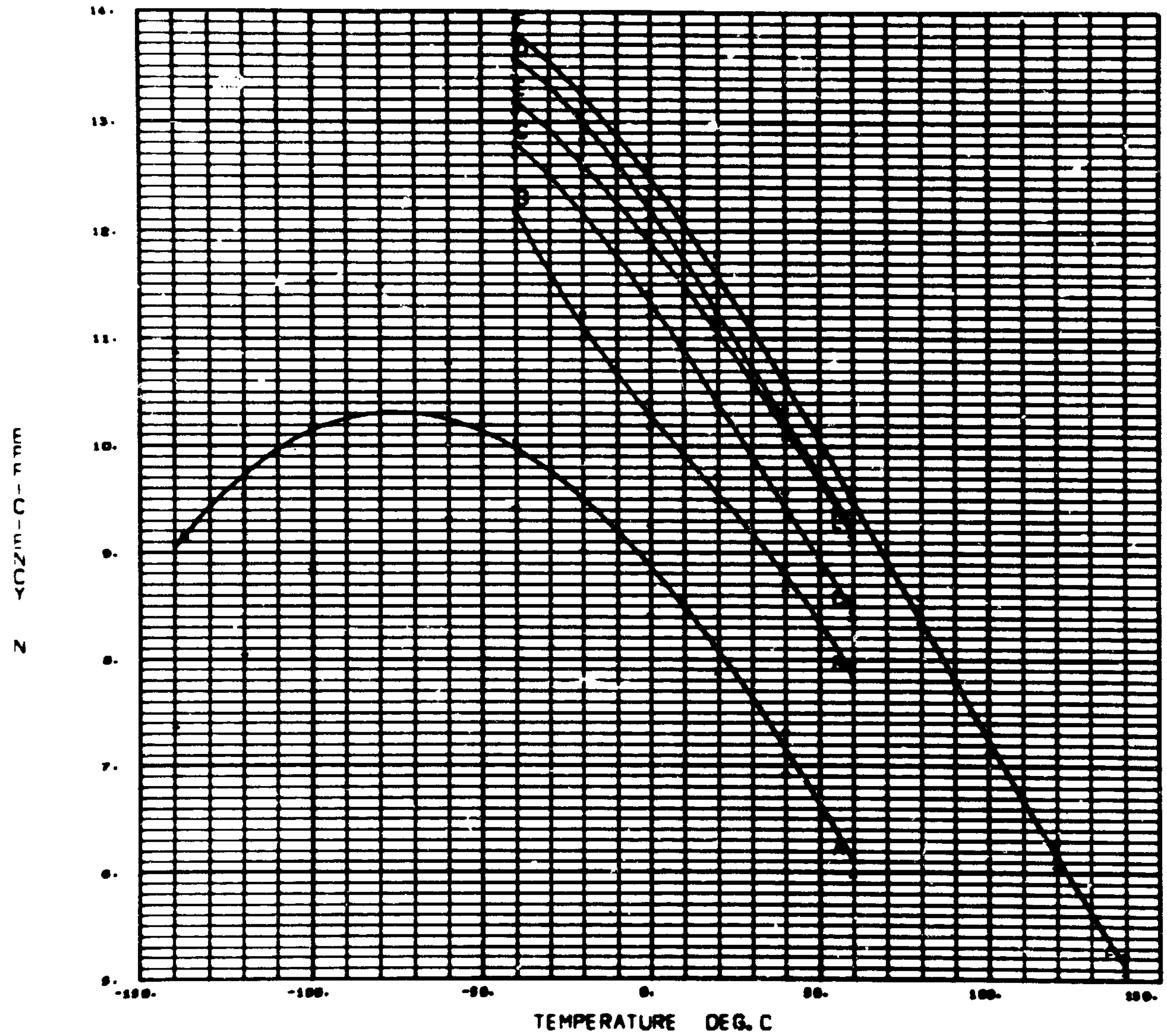
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate B



CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

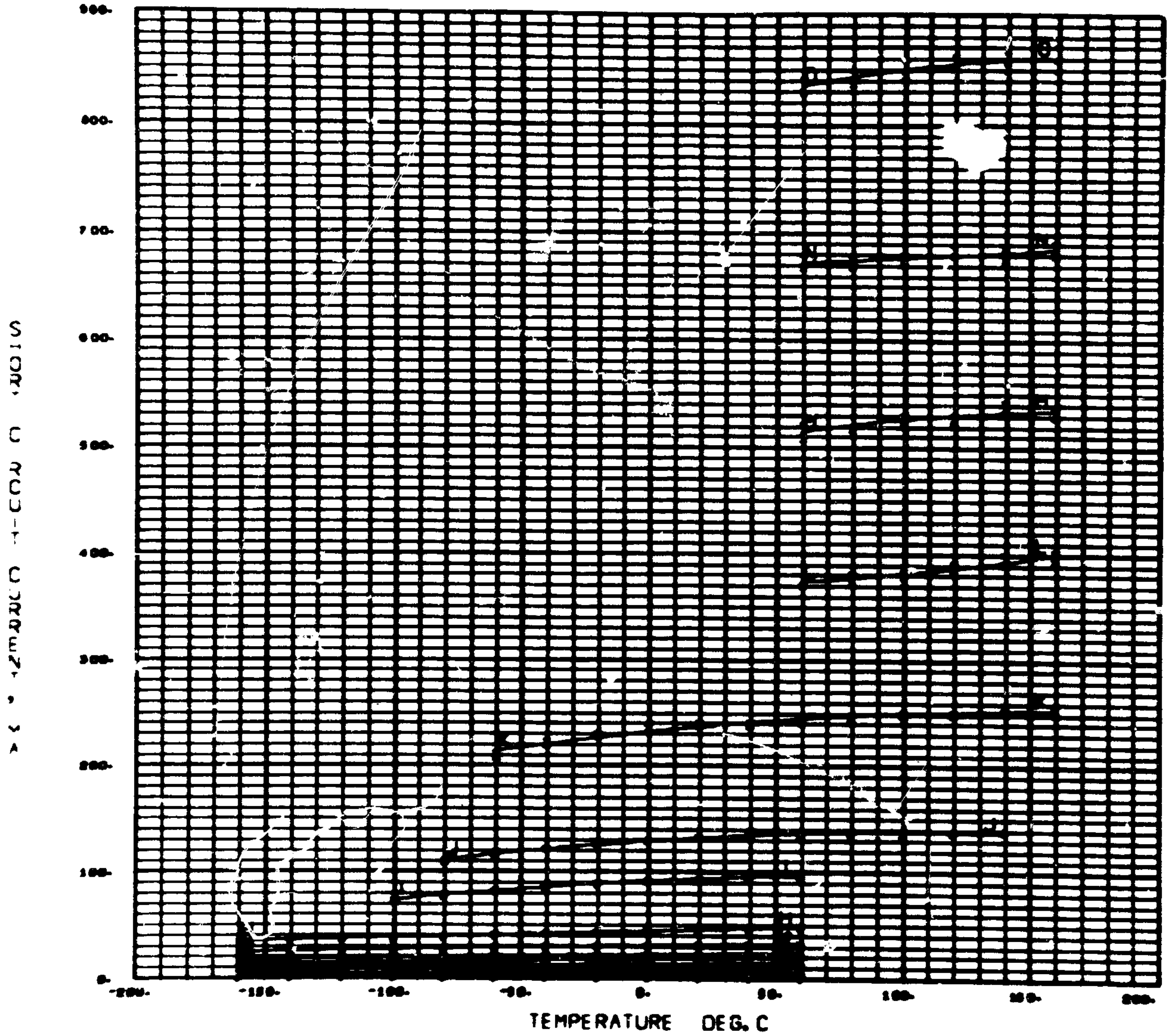
Plate B



N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AG-PD-TI-SOLDERLESS (PLATE B)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate C

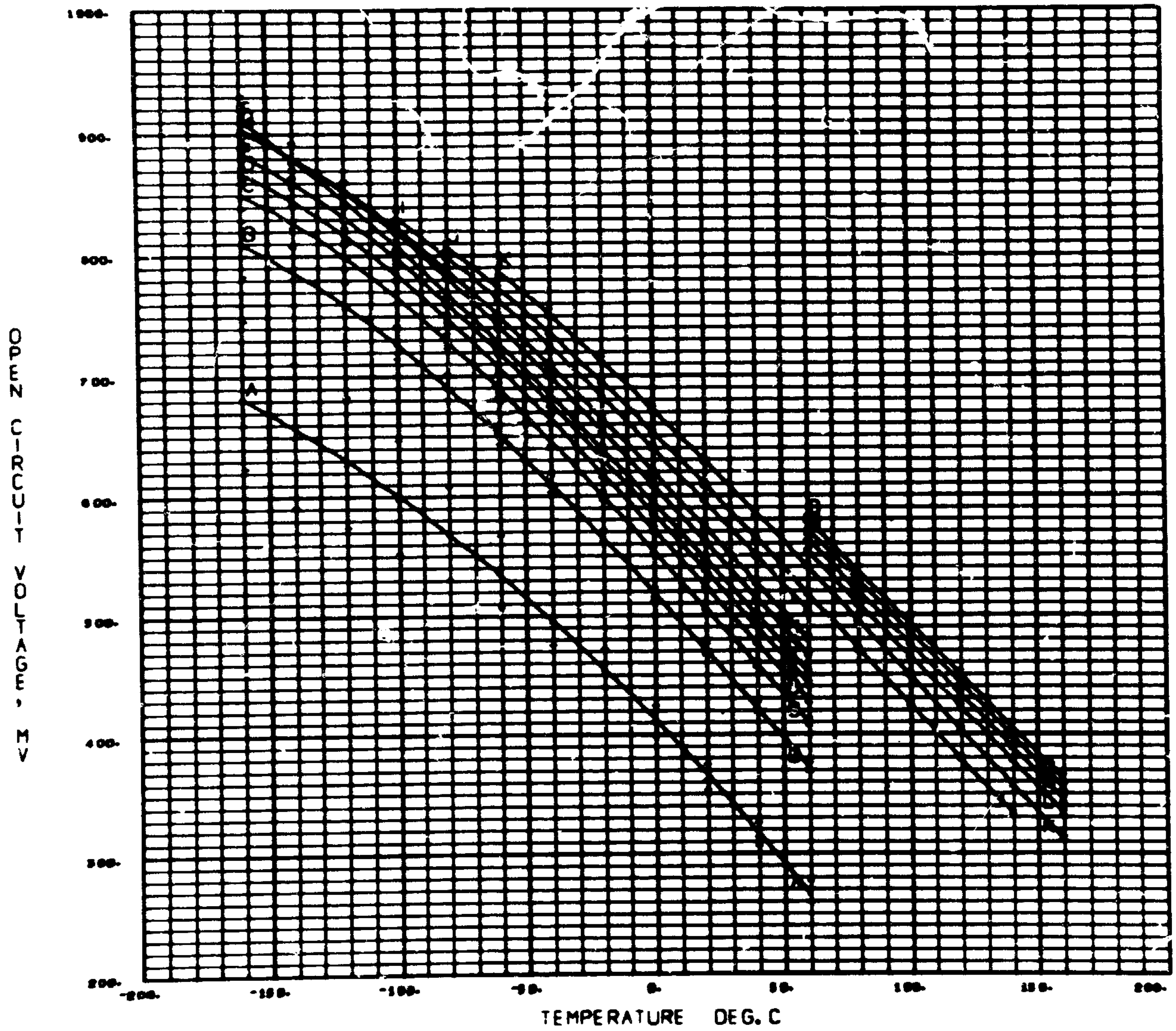


N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEX AG-TI-SOLDER (PLATE C) (M-71)

CURVE ID	A	B	C	D	E	F	G	H
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571

CURVE ID	I	J	K	L	M	N	O
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

Plate C

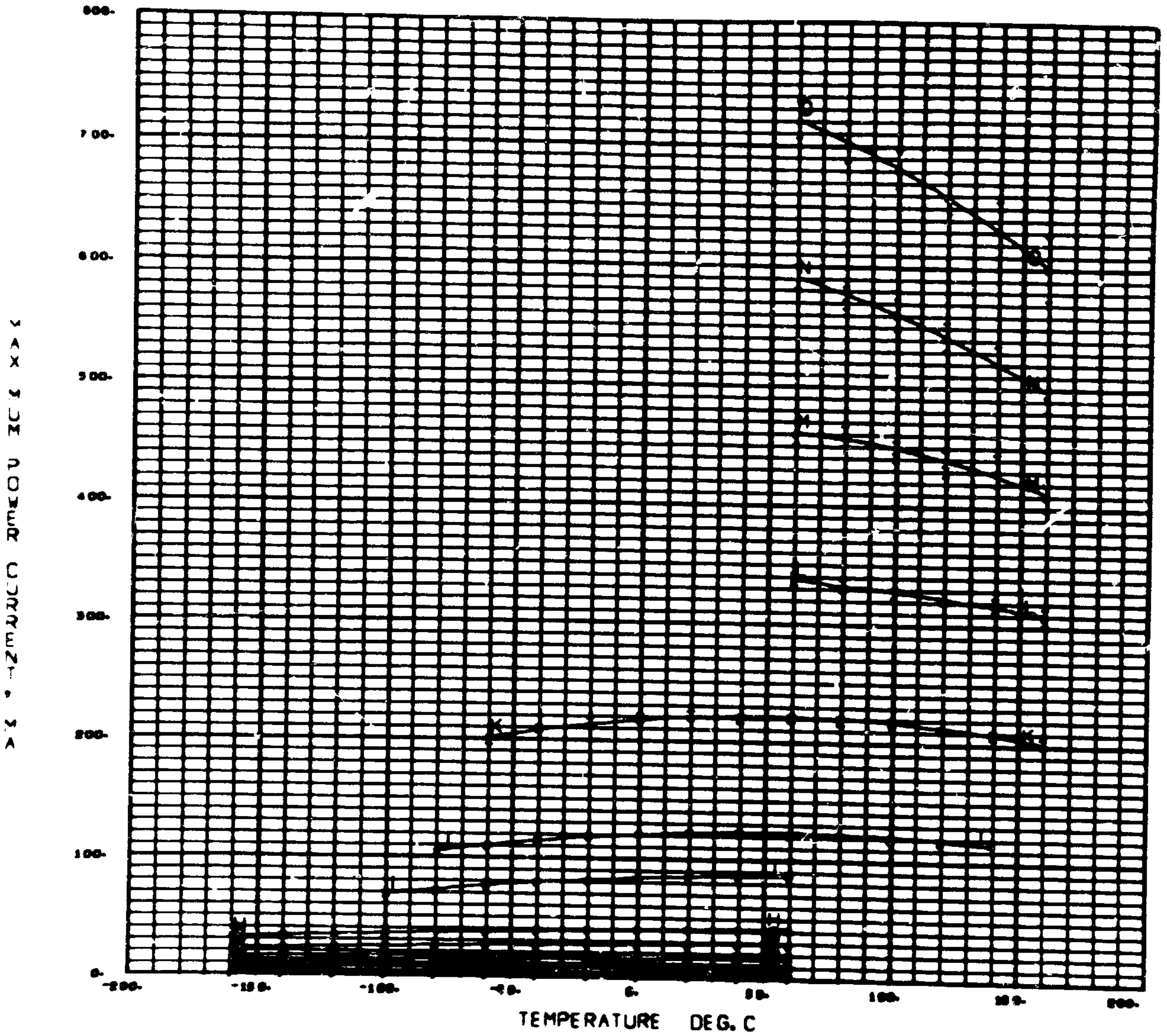


N/P, 2 OHM-CM 2X2 CM SI. SOLAR CELLS SILICON THICKNESS .0180 INCHES HEX AB-TI-SOLDER (PLATE C) (= 7:1)

CURVE ID	A	B	C	D	E	F	G	H
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571

CURVE ID	I	J	K	L	M	N	O
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

Plate C

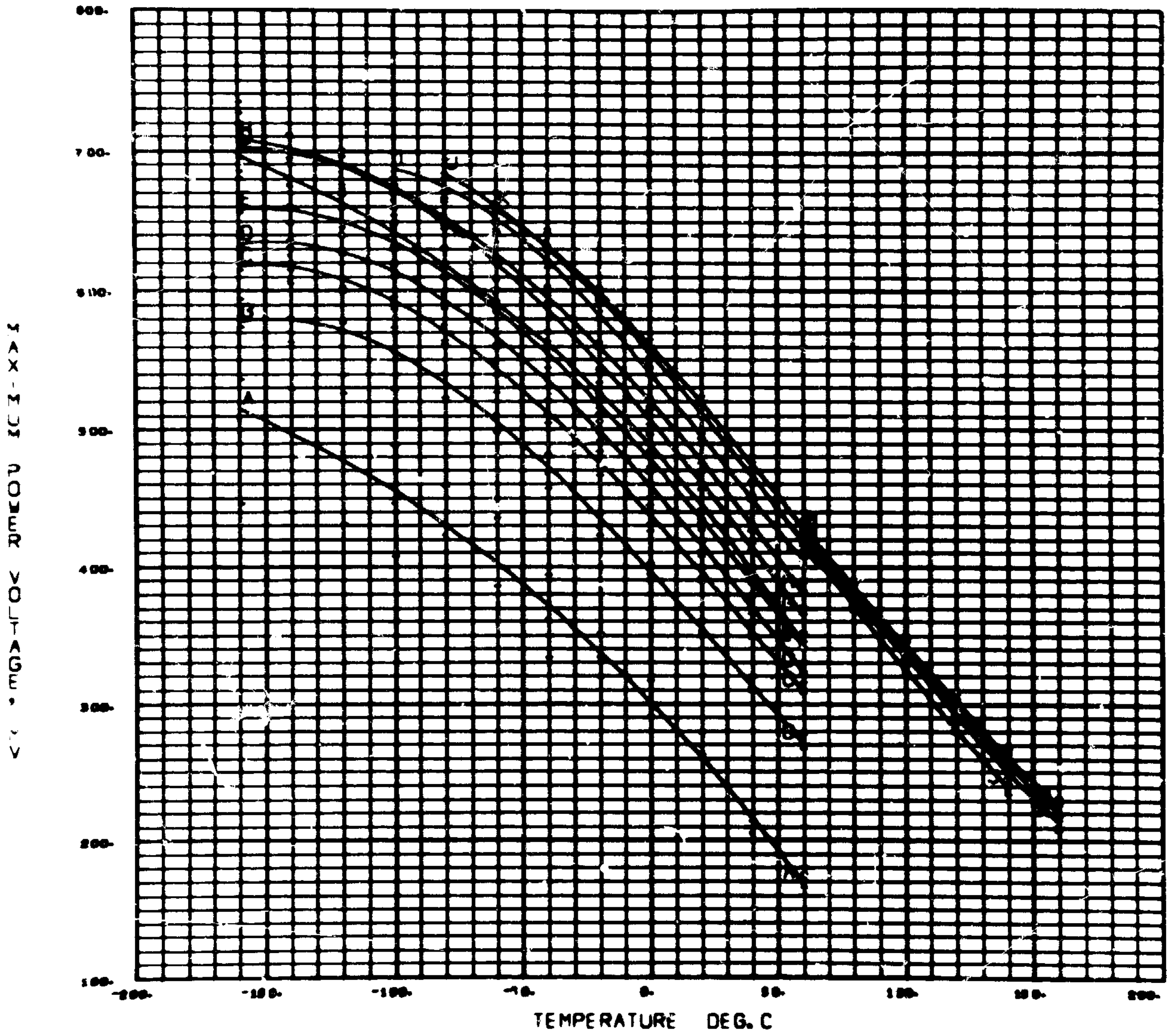


N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AB-TI-SOLDER (PLATE C) (M-71)

CURVE ID	A	B	C	D	E	F	G	H
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571

CURVE ID	I	J	K	L	M	N	O
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

Plate C

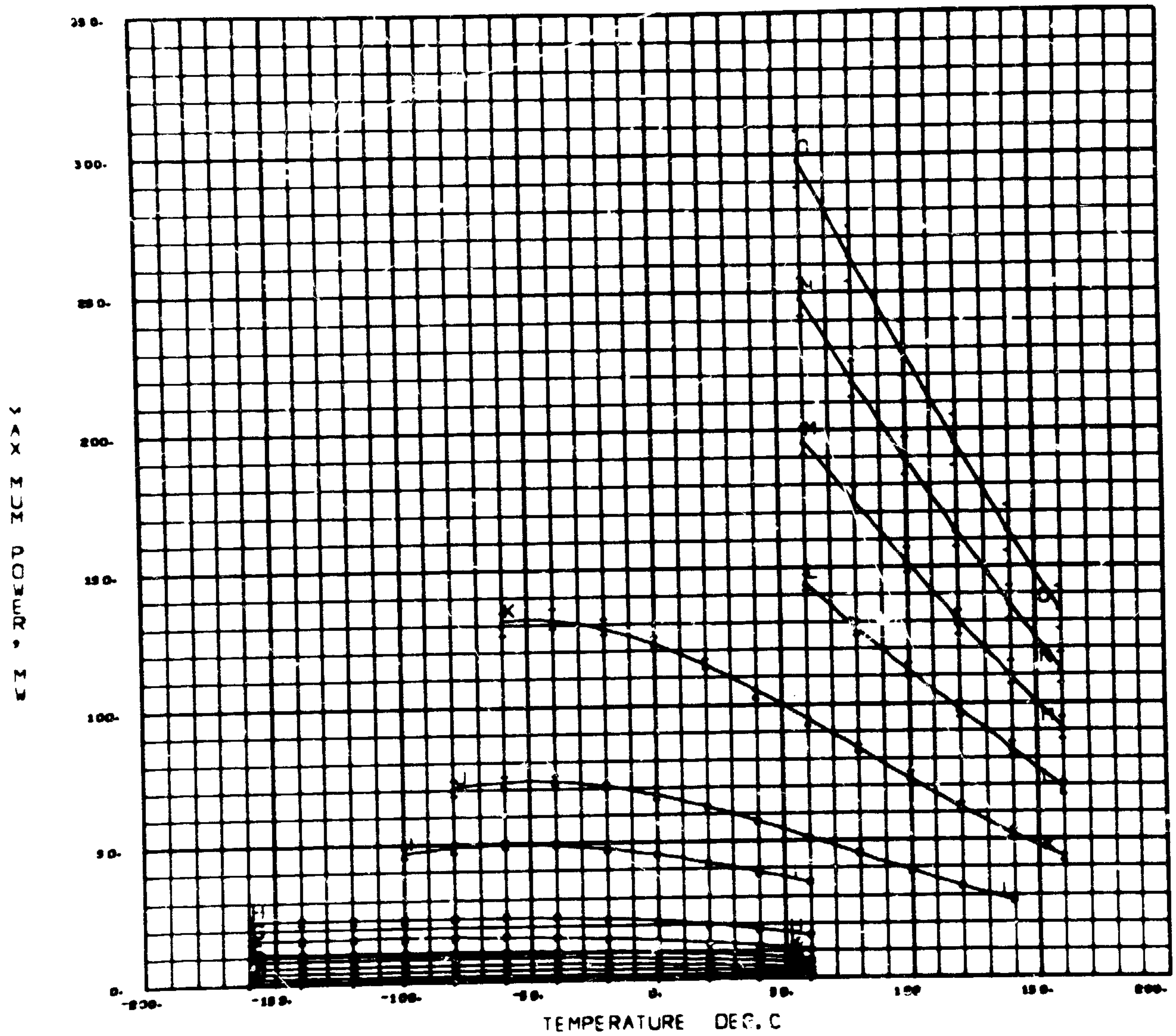


N/P, 2 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AB-TI-SOLDER (PLATE C)

CURVE ID	A	B	C	D	E	F	G	H
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571

CURVE ID	I	J	K	L	M	N	O
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

Plate C

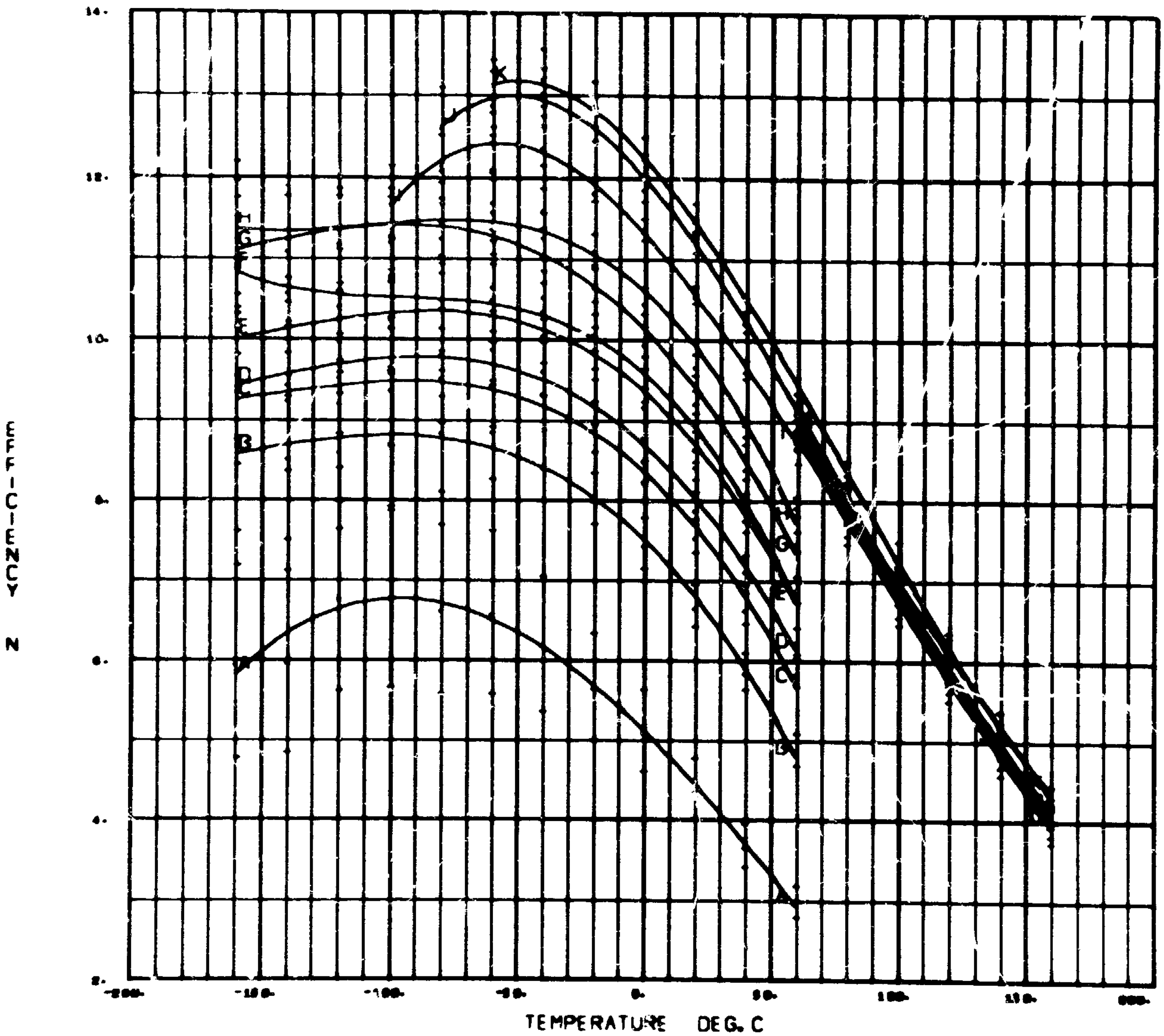


N/P, 2 OHM-CM, 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AG-TI-SOLDER (PLATE C) (M 71)

CURVE ID	A	B	C	D	E	F	G	H
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571

CURVE ID	I	J	K	L	M	N	O
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

Plate C

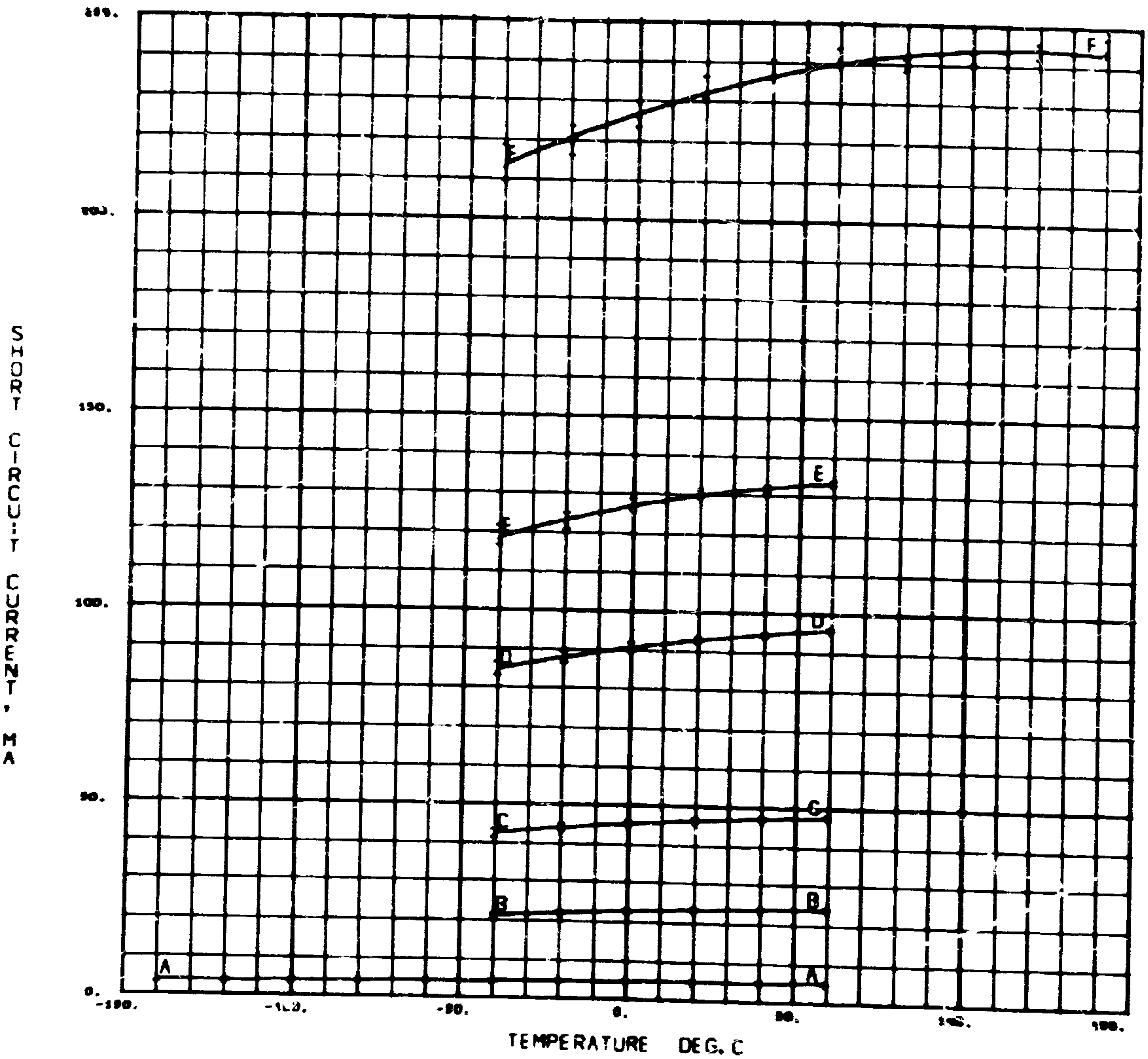


N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AG-TI-SOLDER (PLATE C) (H-71)

CURVE ID	A	B	C	D	E	F	G	H
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571

CURVE ID	I	J	K	L	M	N	O
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

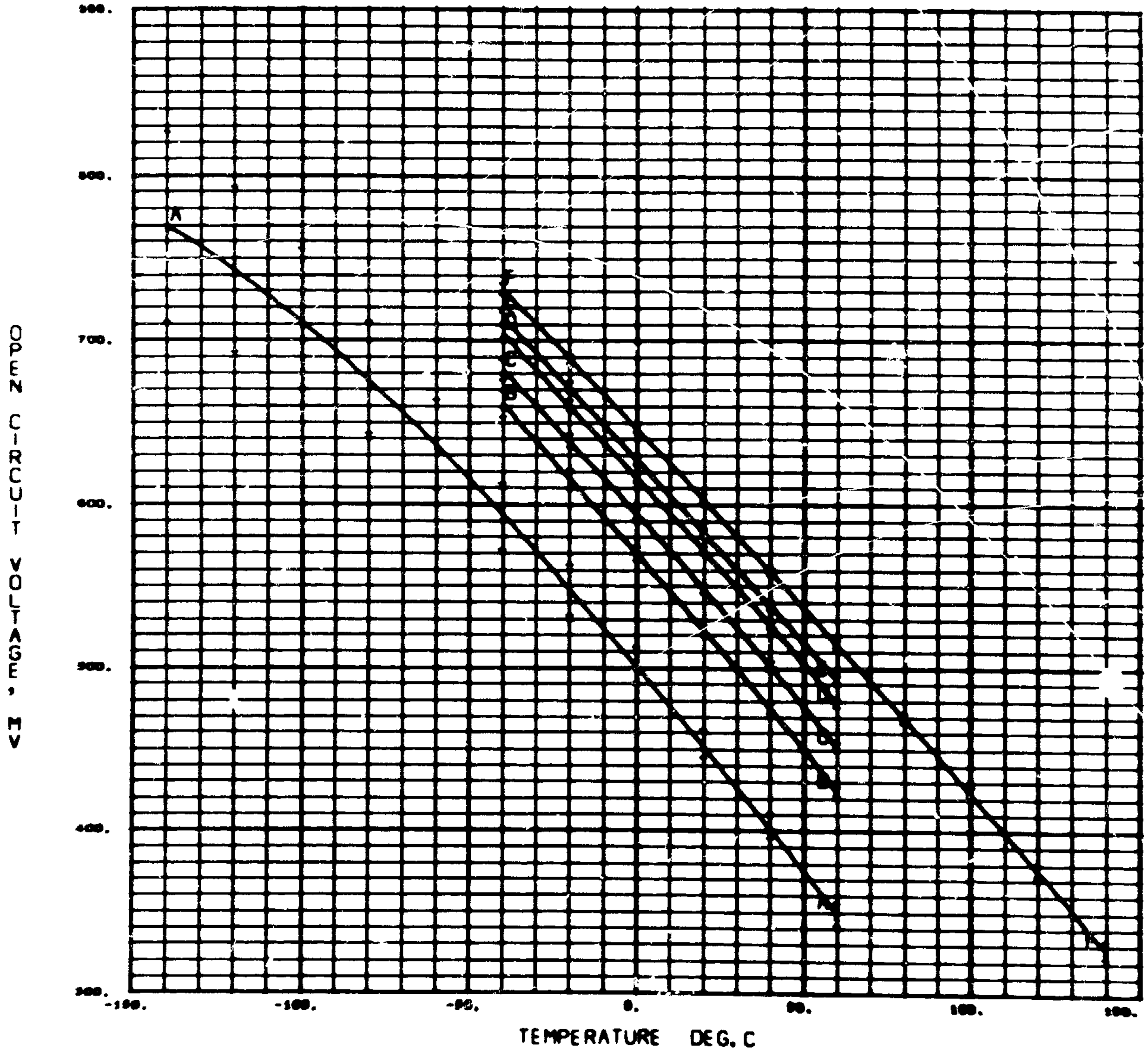
Plate D



P/N 1 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AG-TI-SOLDER CRNR DART (PLATE I

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

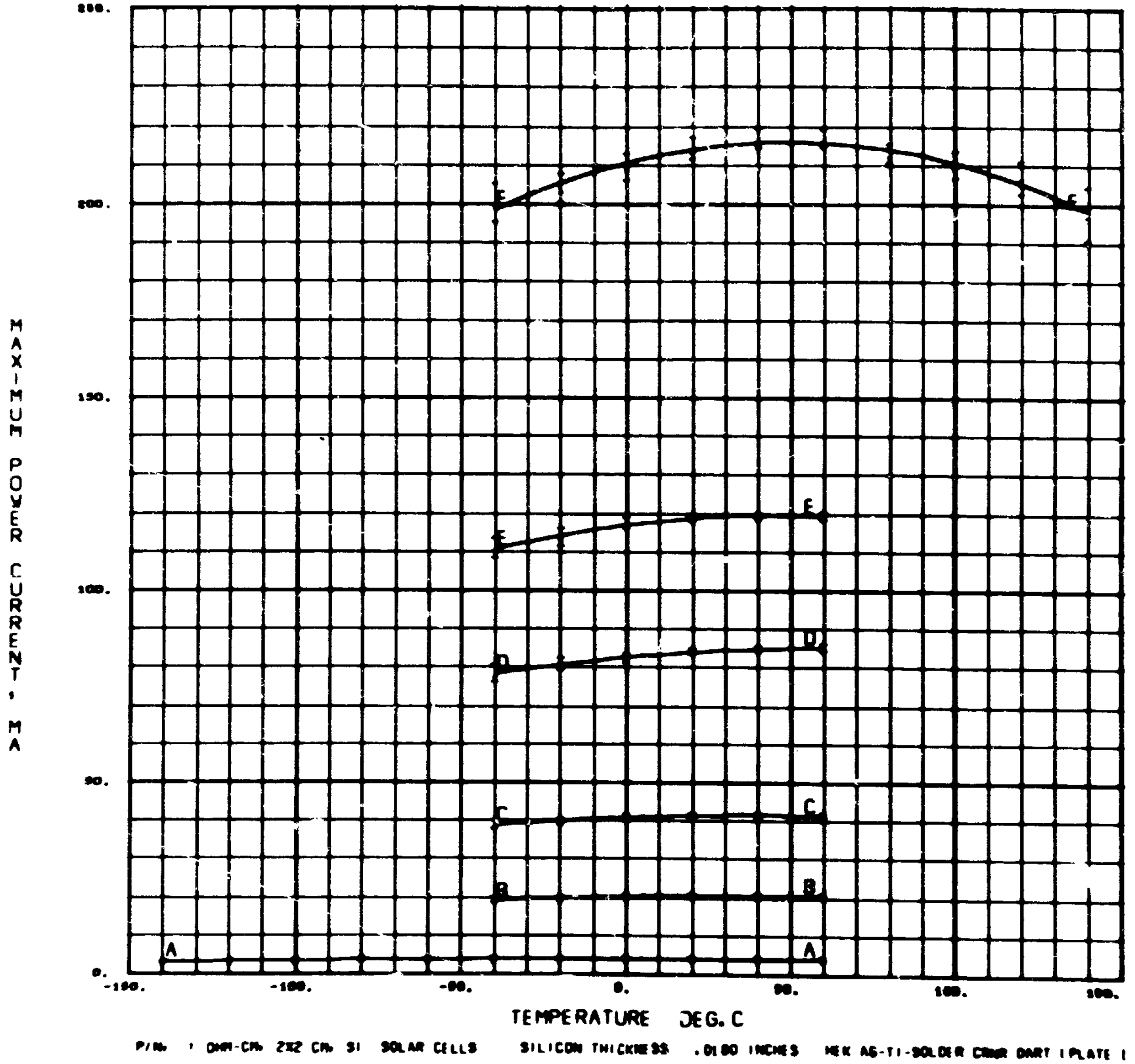
Plate D



P/N 1 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0190 INCHES HEX AG-TI-SOLDER CRNR DEPT (PLATE D)

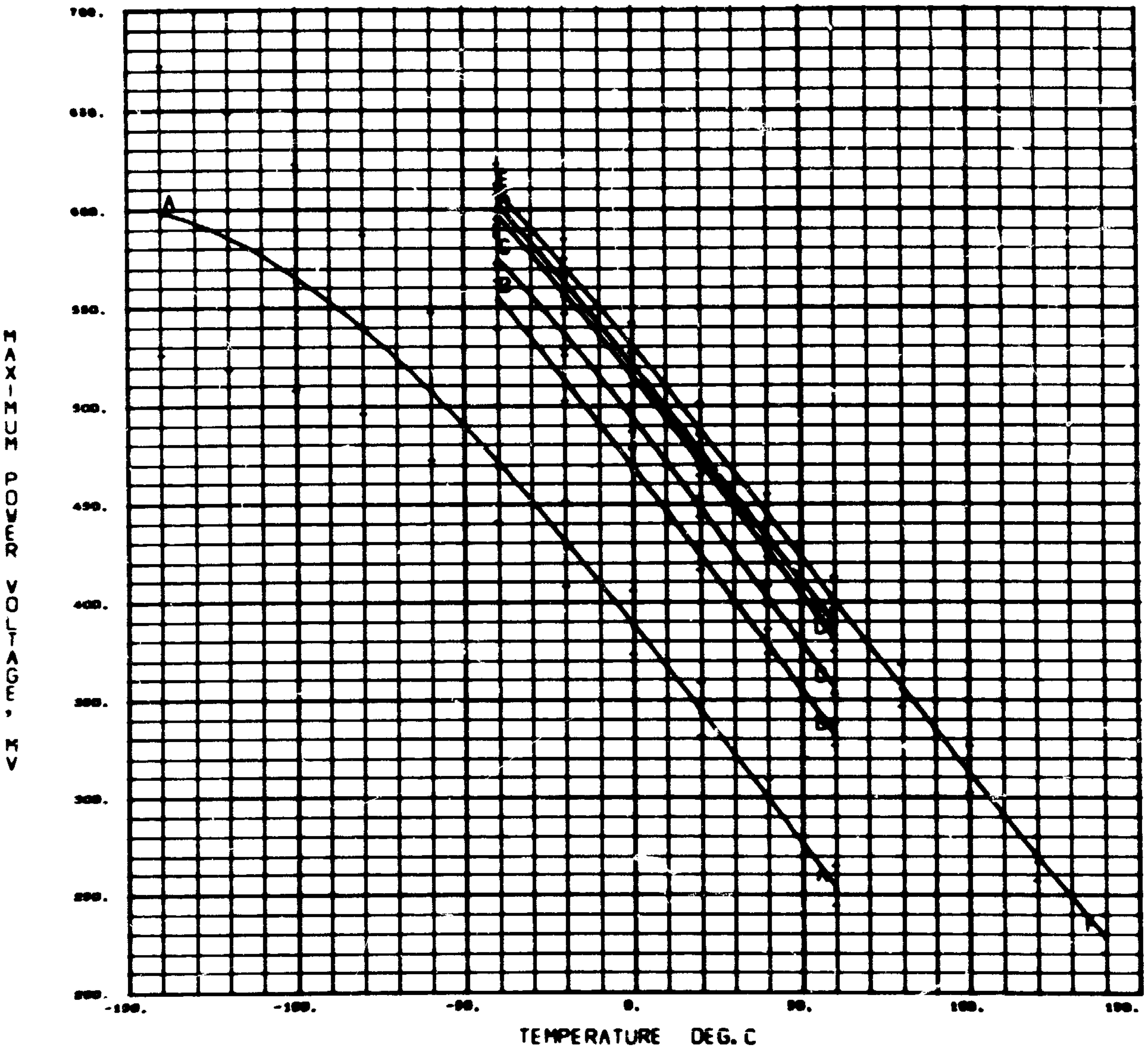
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate D



CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

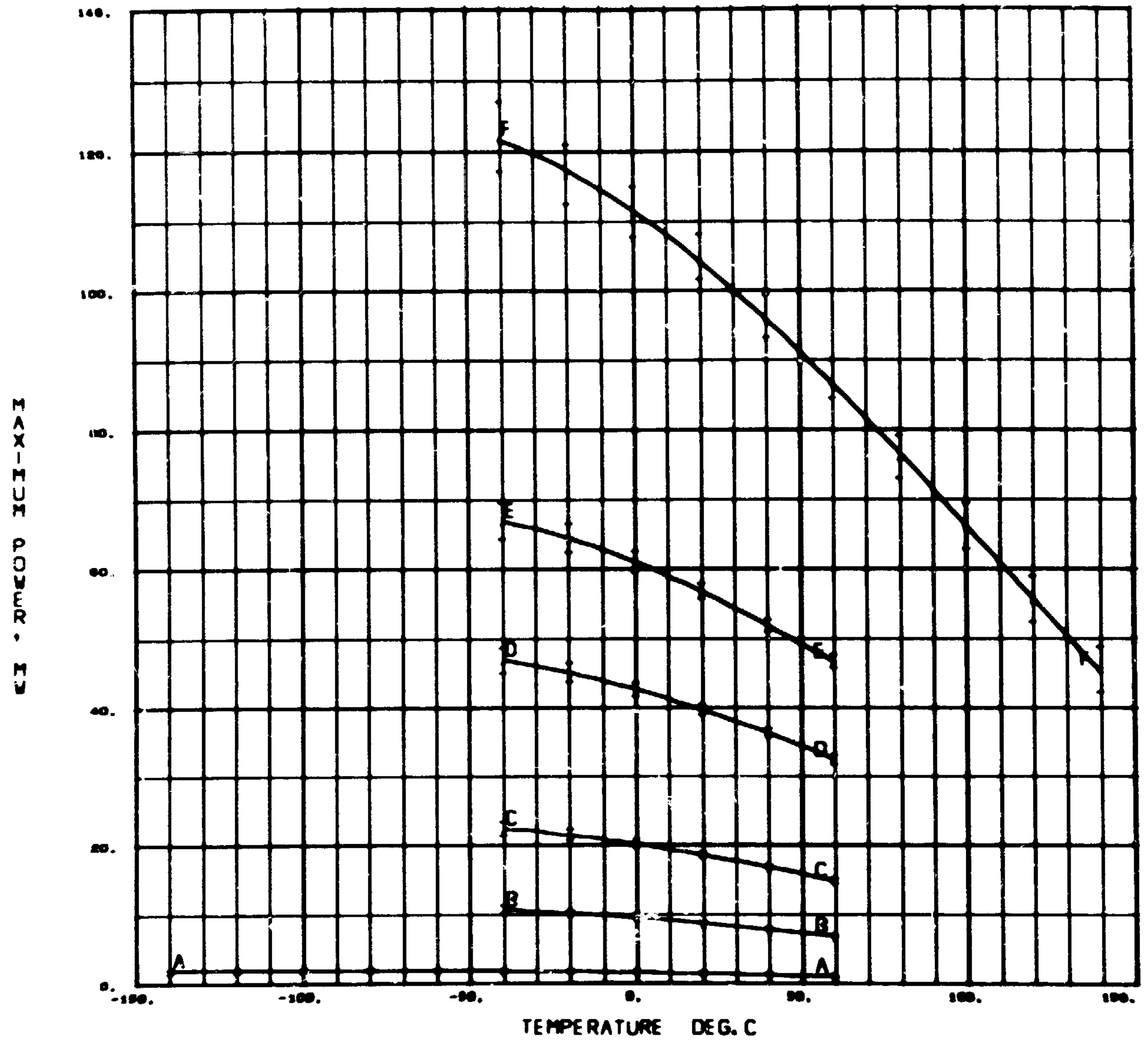
Plate D



P/N 1 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEK AG-TI-SOLDER CRNR BART (PLATE)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

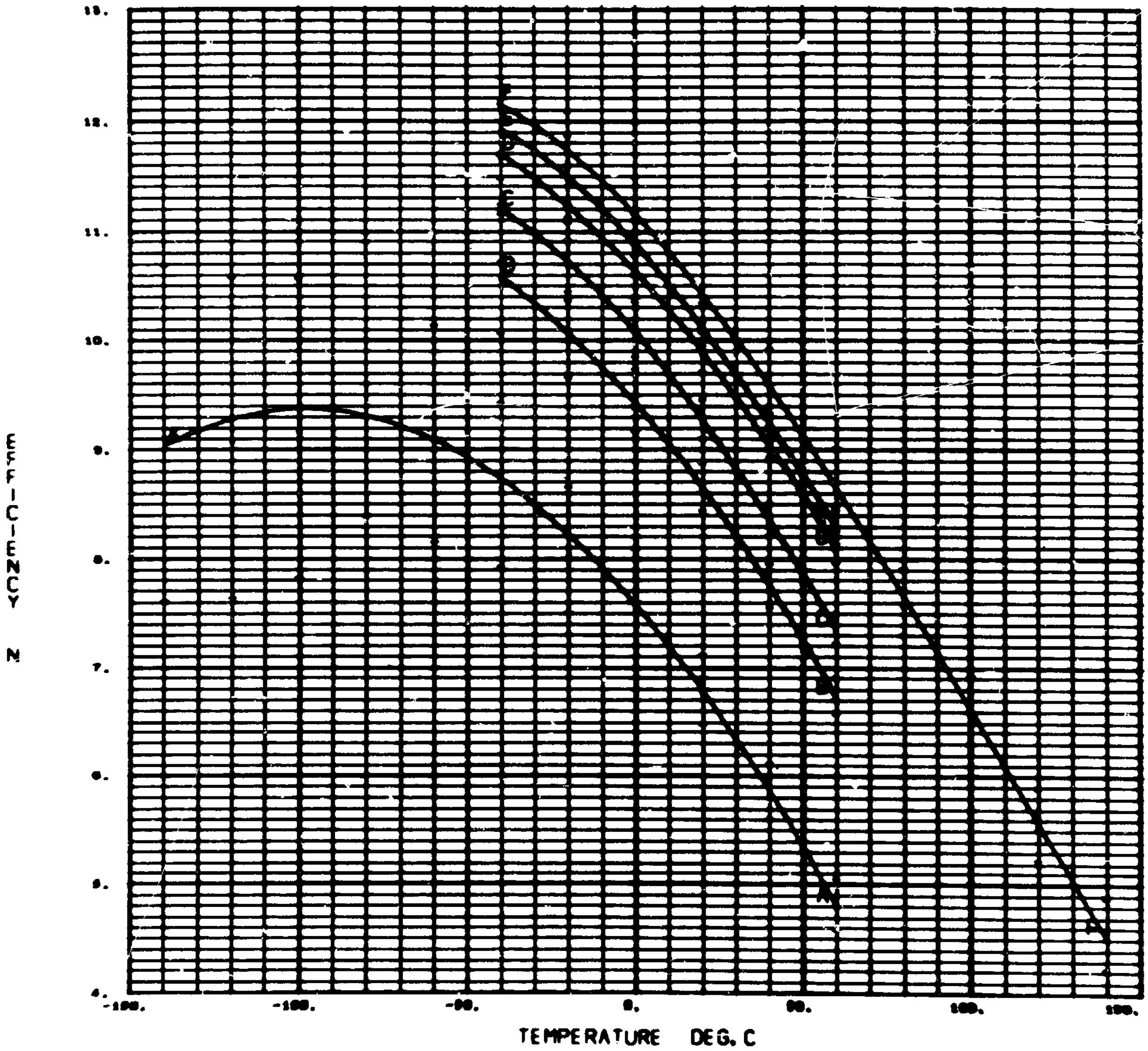
Plate D



P/N 1 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEX AG-TI-SOLDER CRNR DART (PLATE I

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

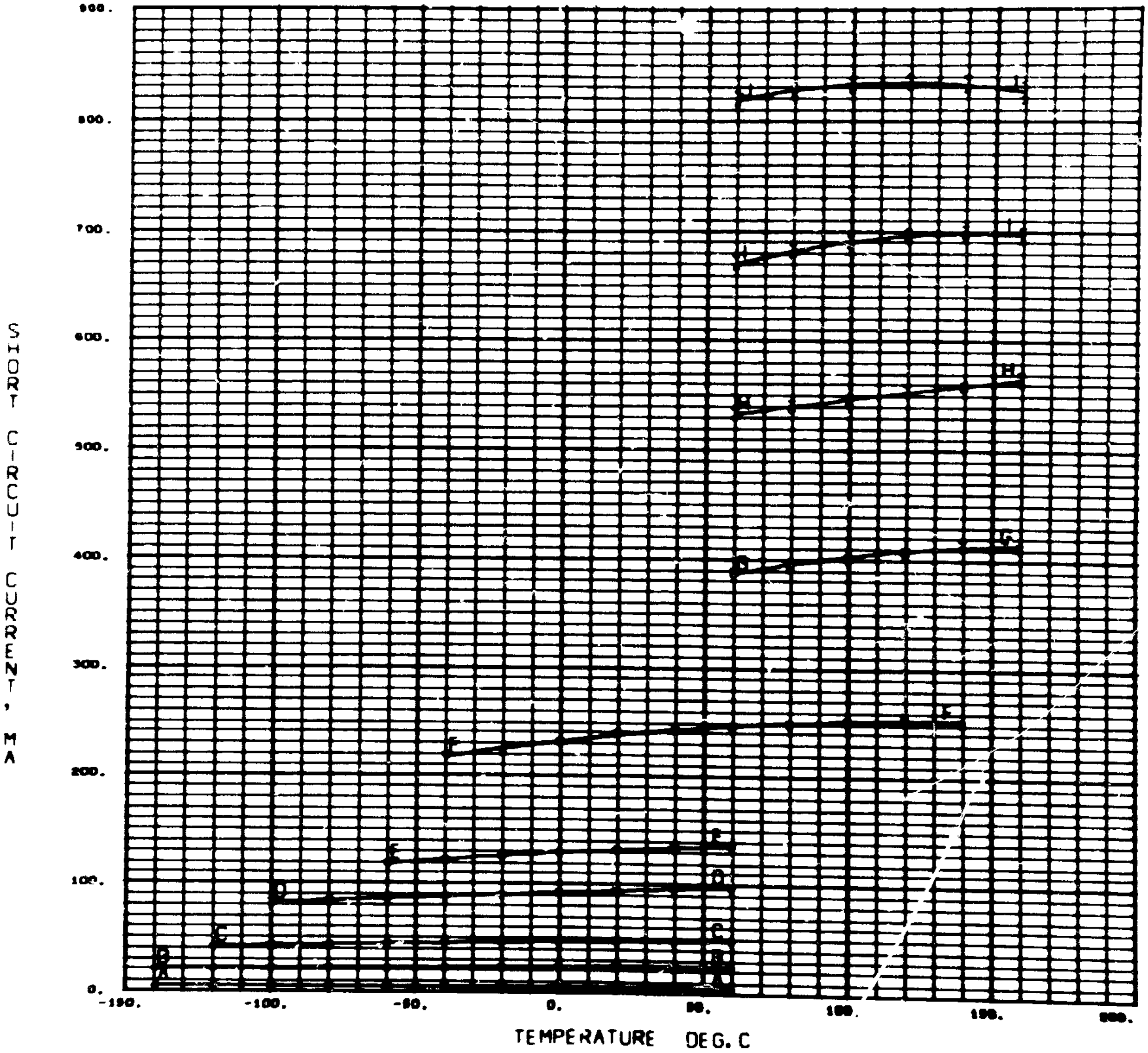
Plate D



P/N 1 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES HEX AG-TI-SOLDER CRNR DART (PLATE I

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

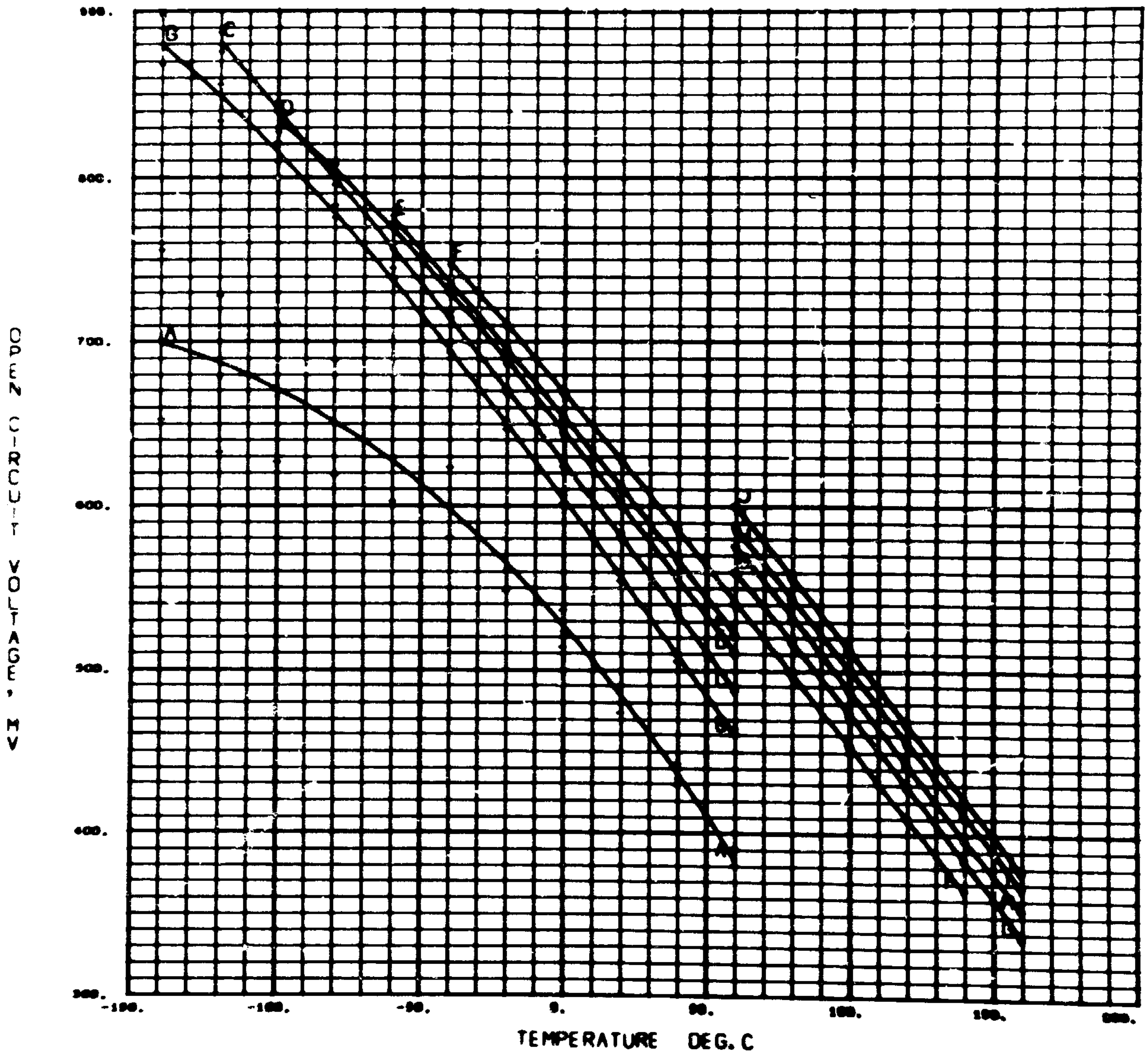
Plate E



N/P, 2 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-PD-TI SOLDERLESS

CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

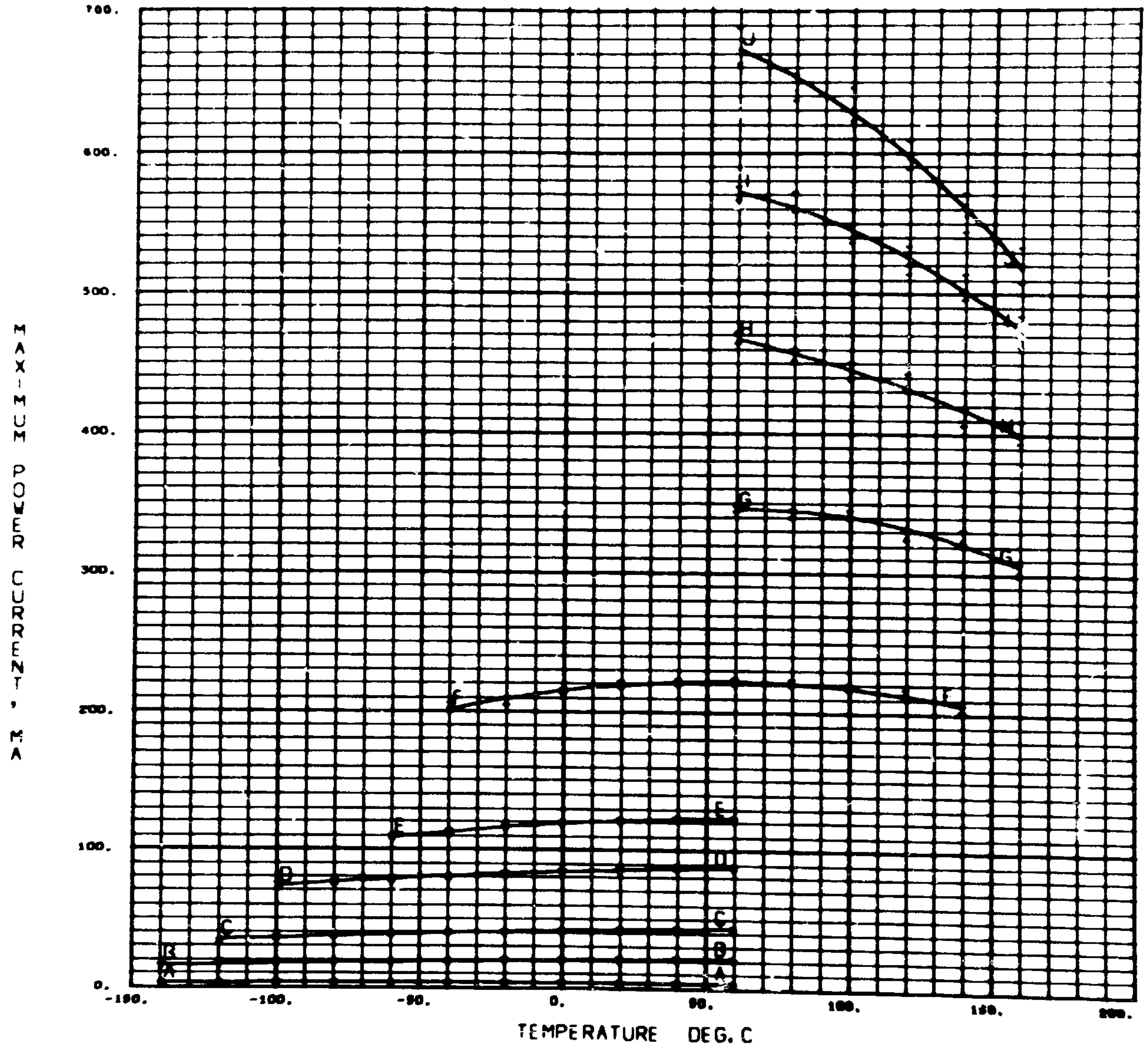
Plate E



N/P, 2 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-PD-TI SOLDERLESS

CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

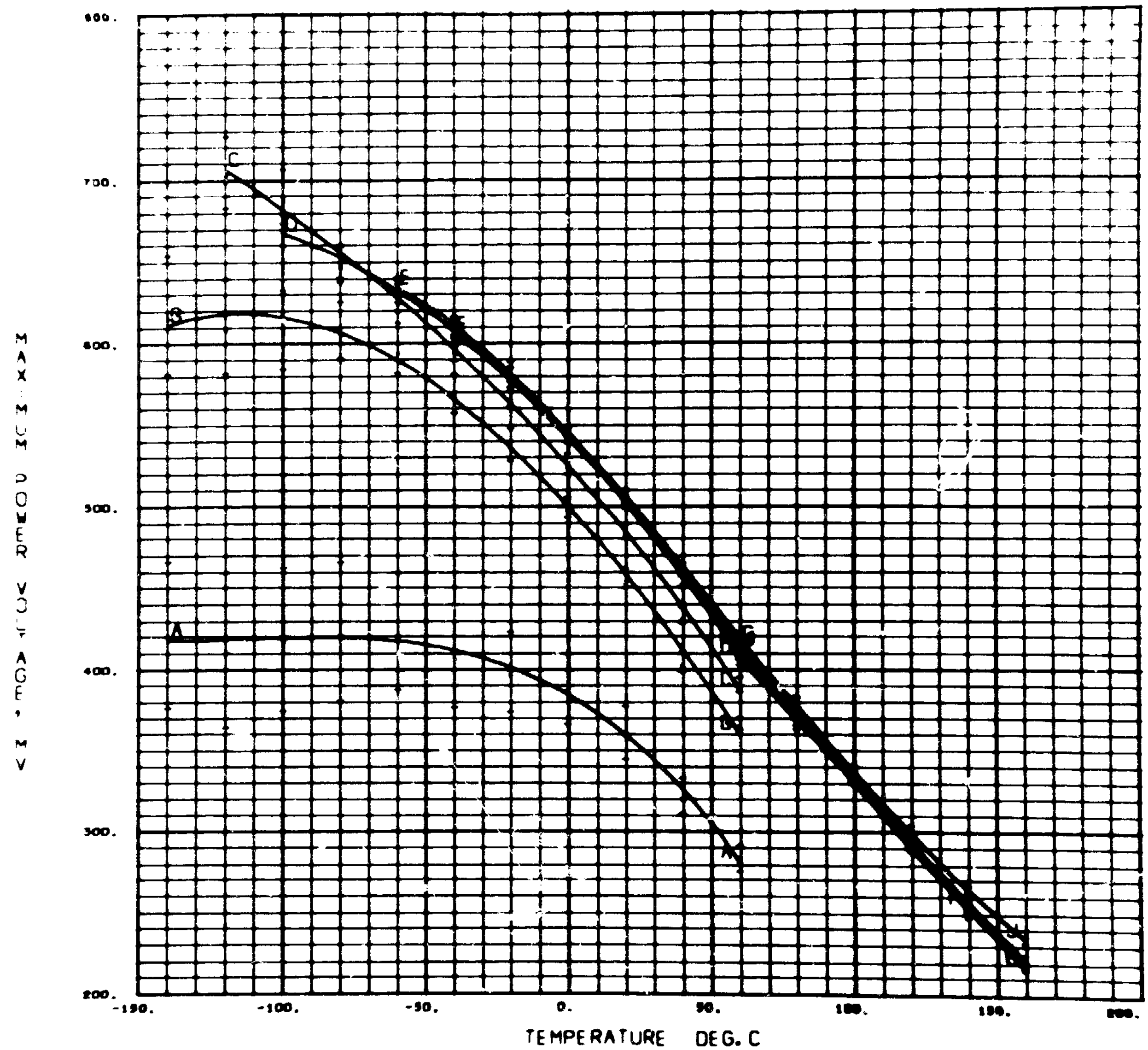
Plate E



N/P. 2 OHM-CM. 2X2 CM. SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-PD-TI SOLDERLESS

CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

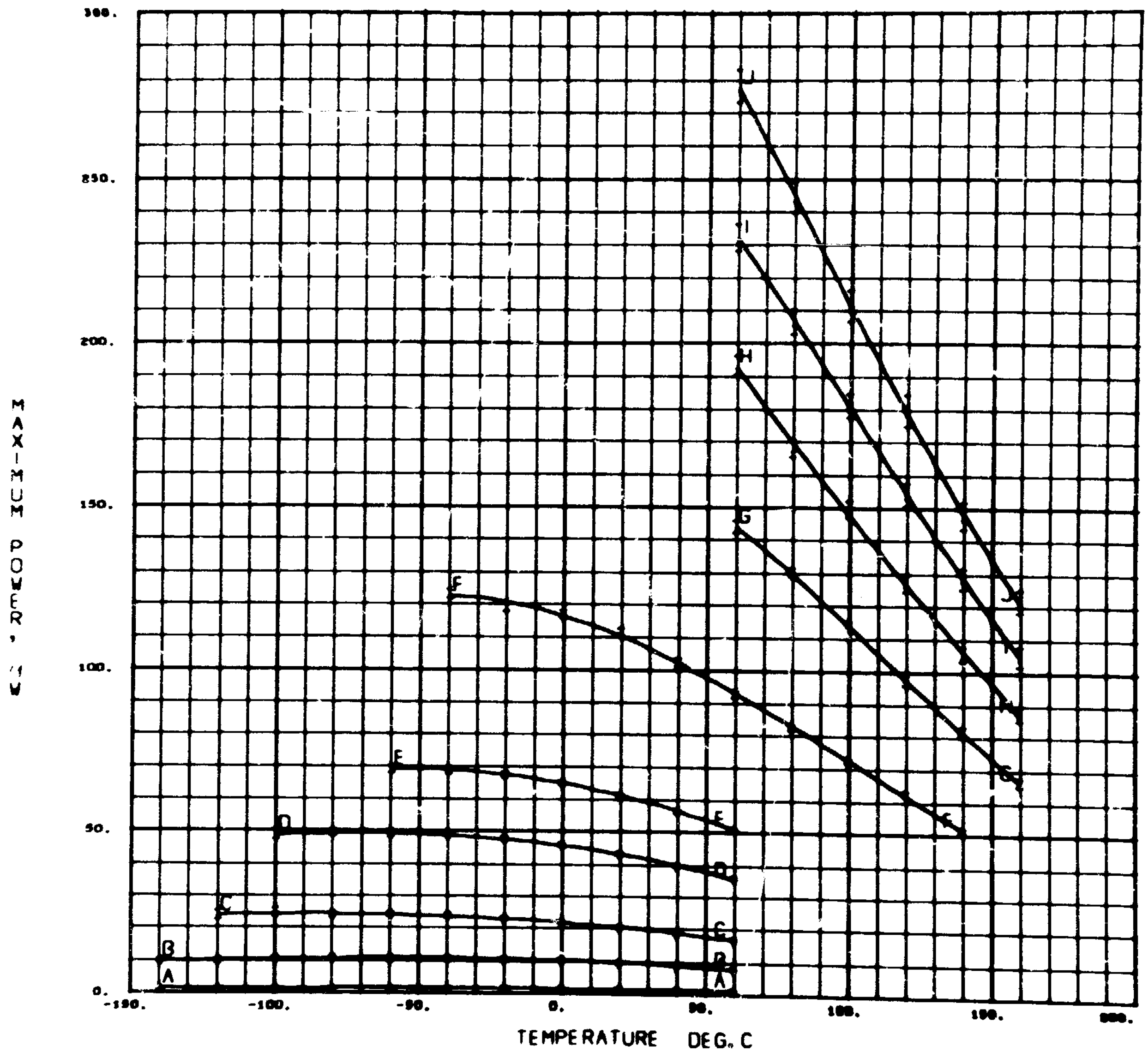
Plate E



N/P, 2 OHM-CM, 2X2 CM. SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AB-PD-TI SOLDERLESS

CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

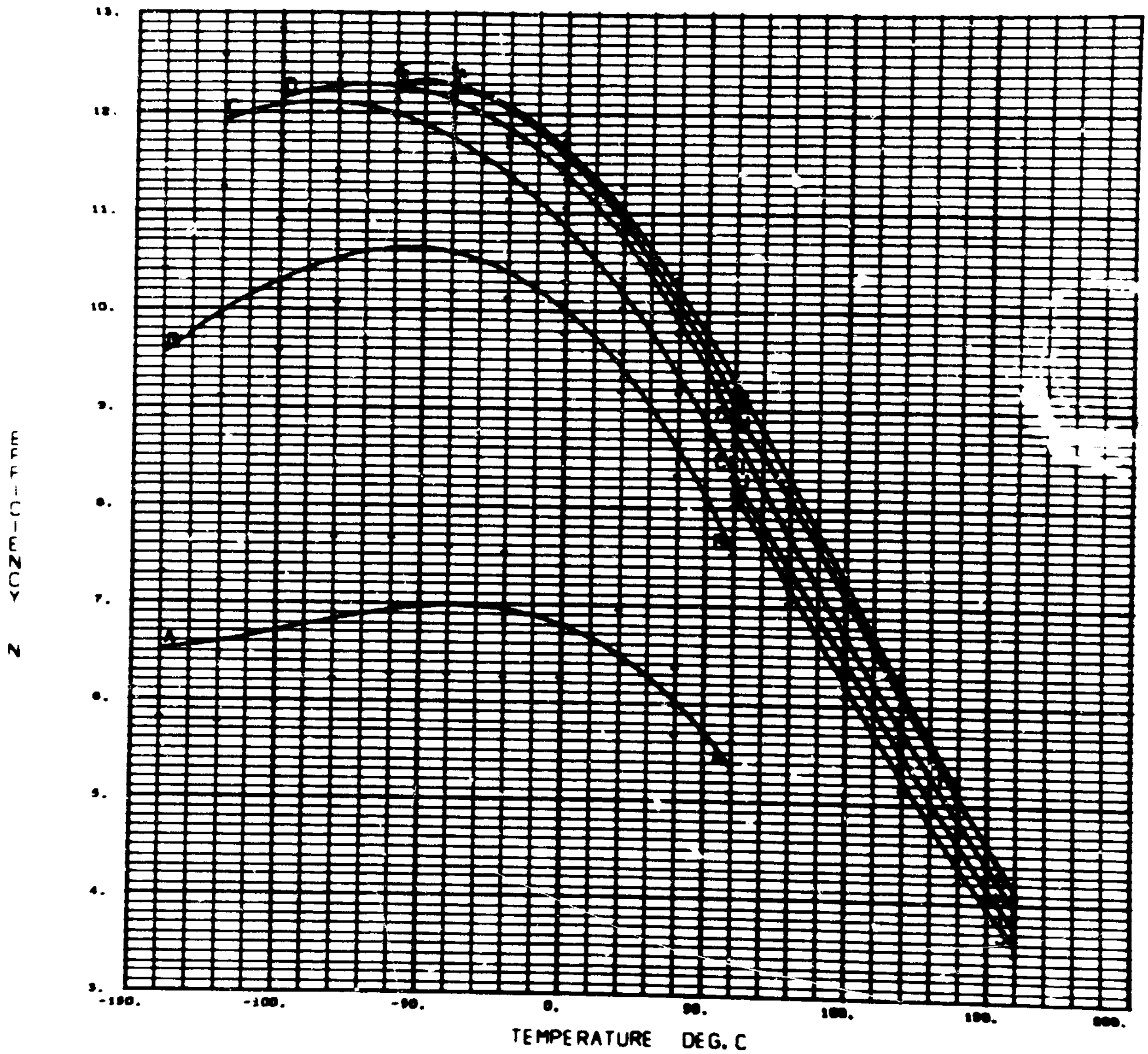
Plate E



N/P, 2 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-PD-TI SOLDERLESS

CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

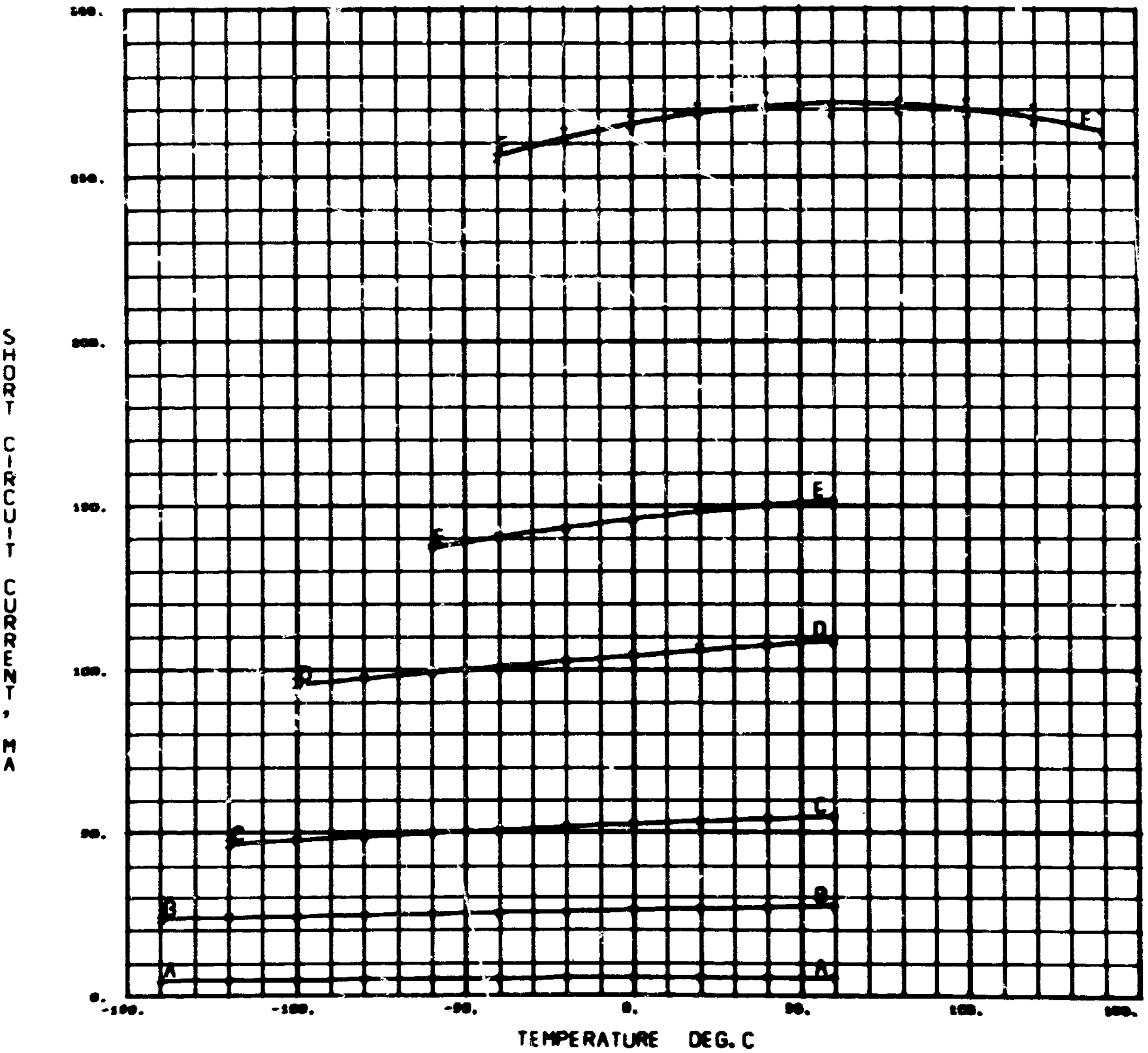
Plate E



N/P, 2 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-PD-TI SOLDERLESS

CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

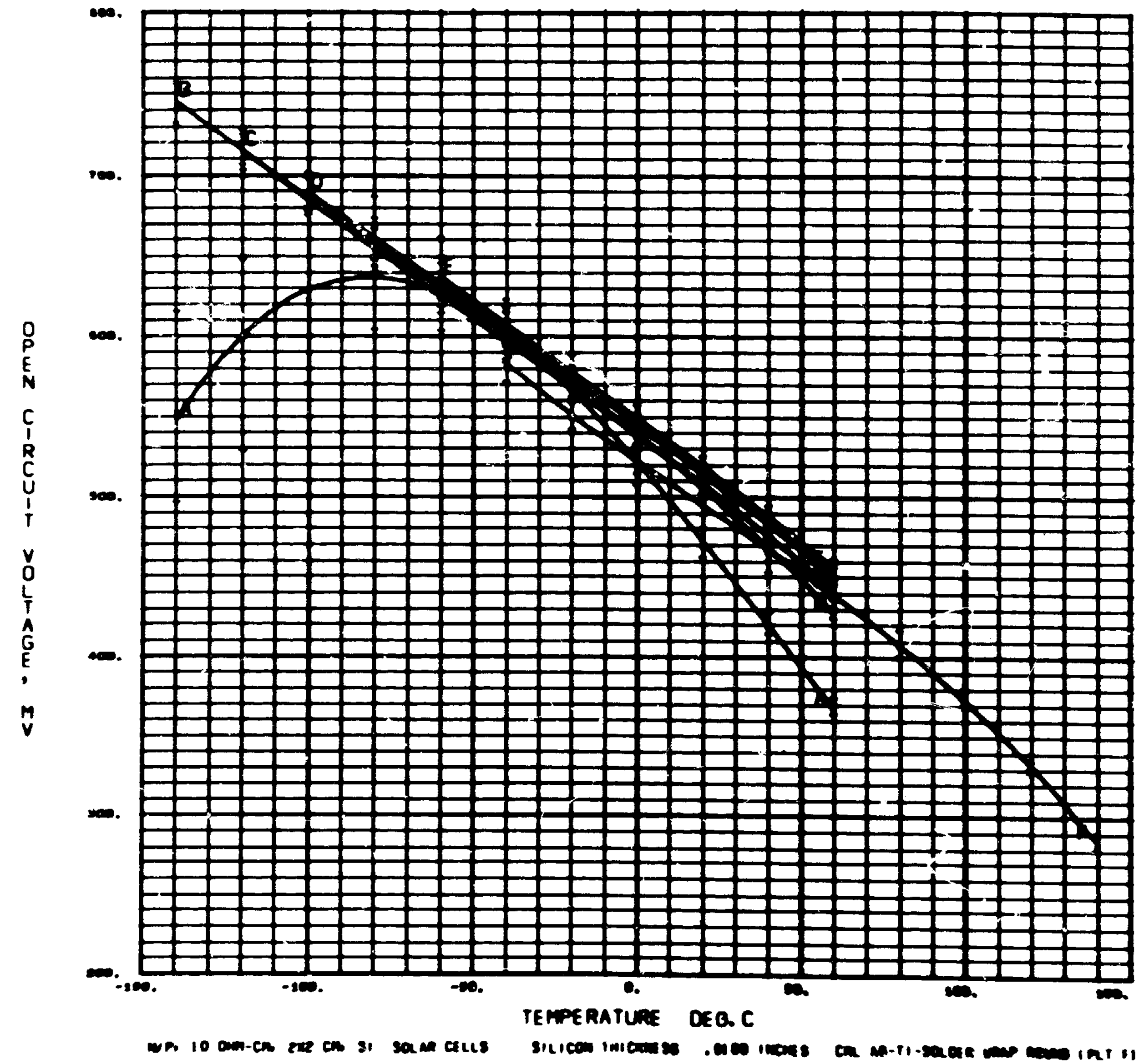
Plate F-1



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-TI-SOLDER WRAP ROUND (PLT F)

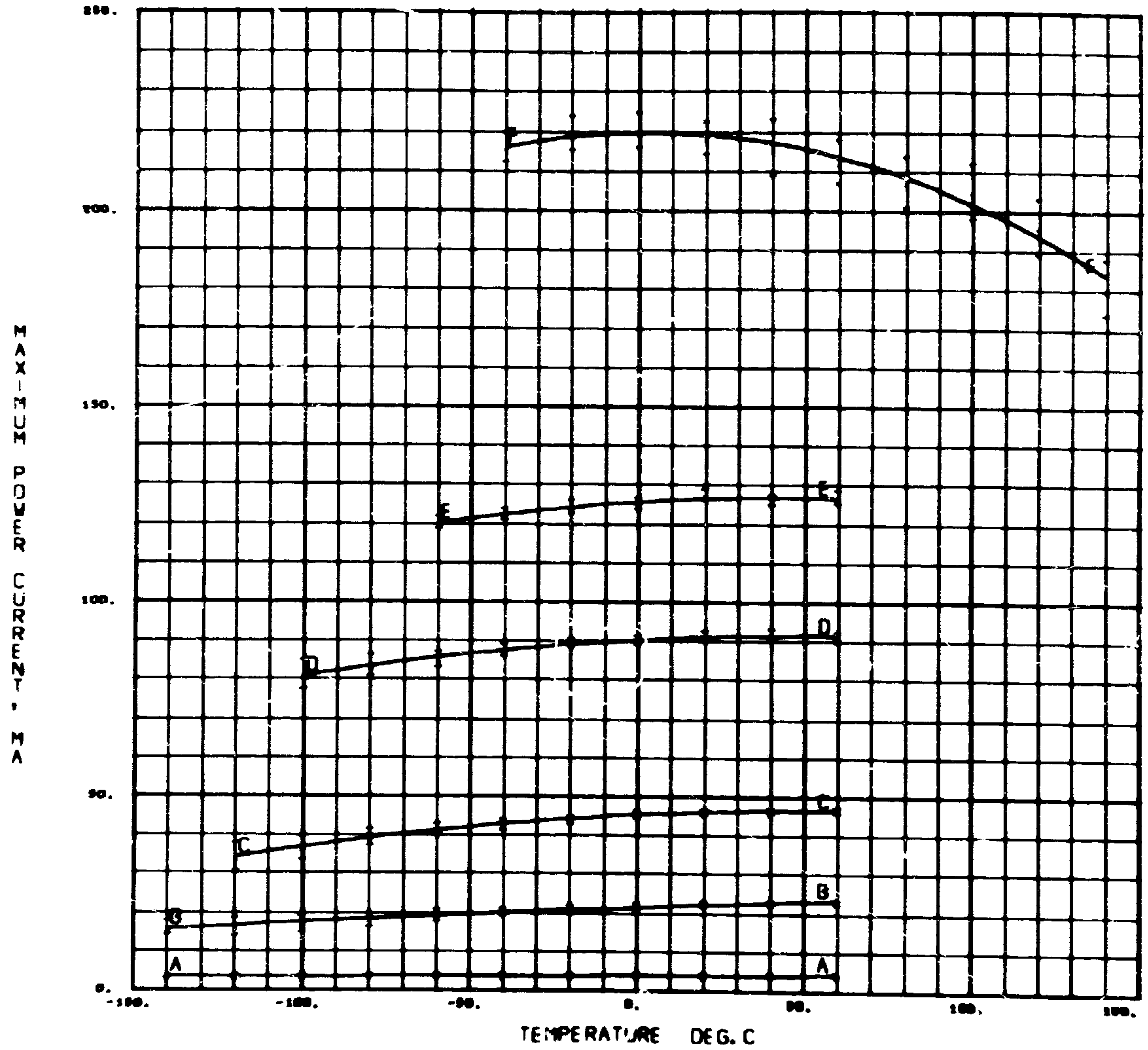
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate F-1



CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

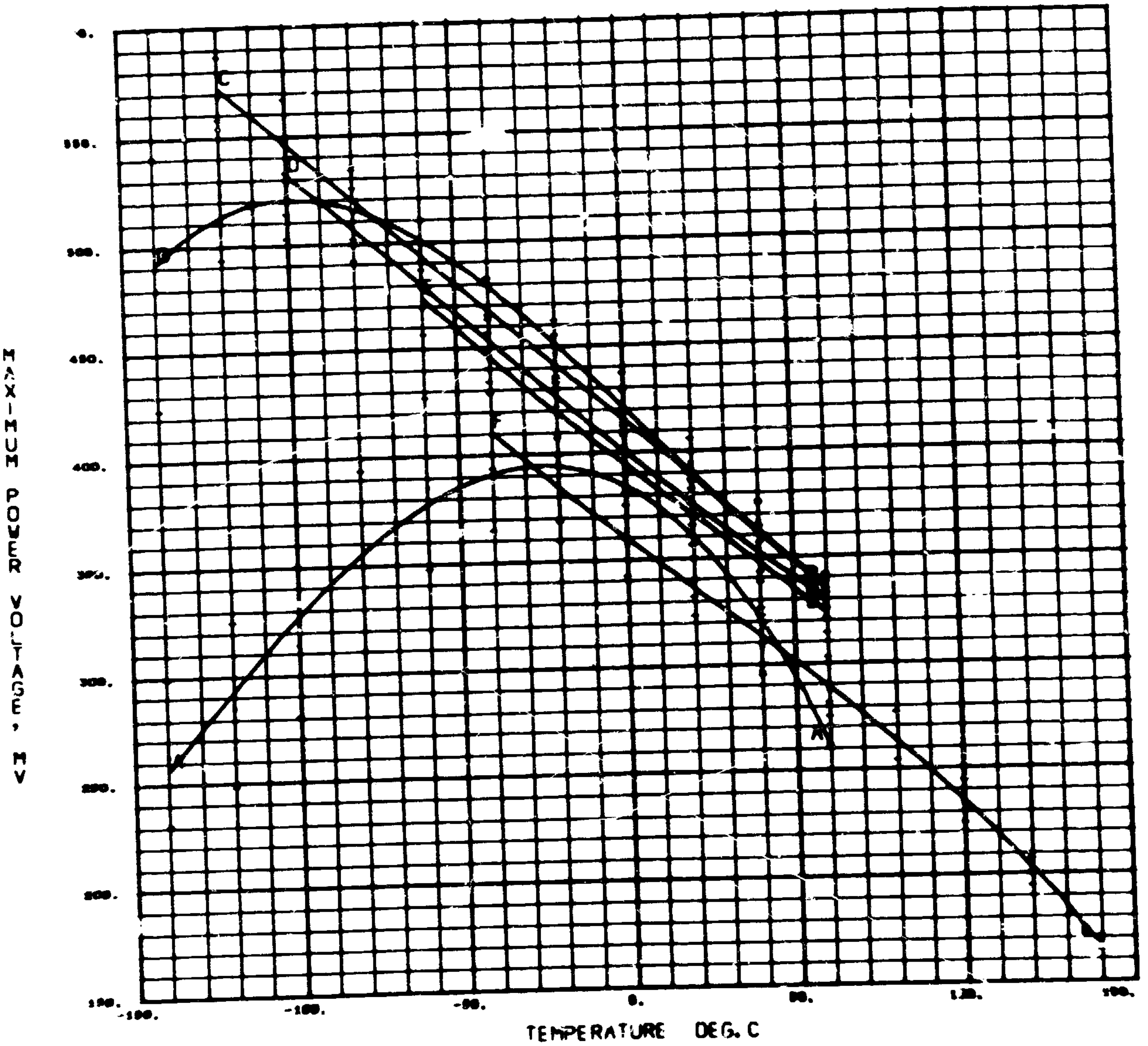
Plate F-1



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-TI-SOLDER WRAP ROUND (PLT F)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

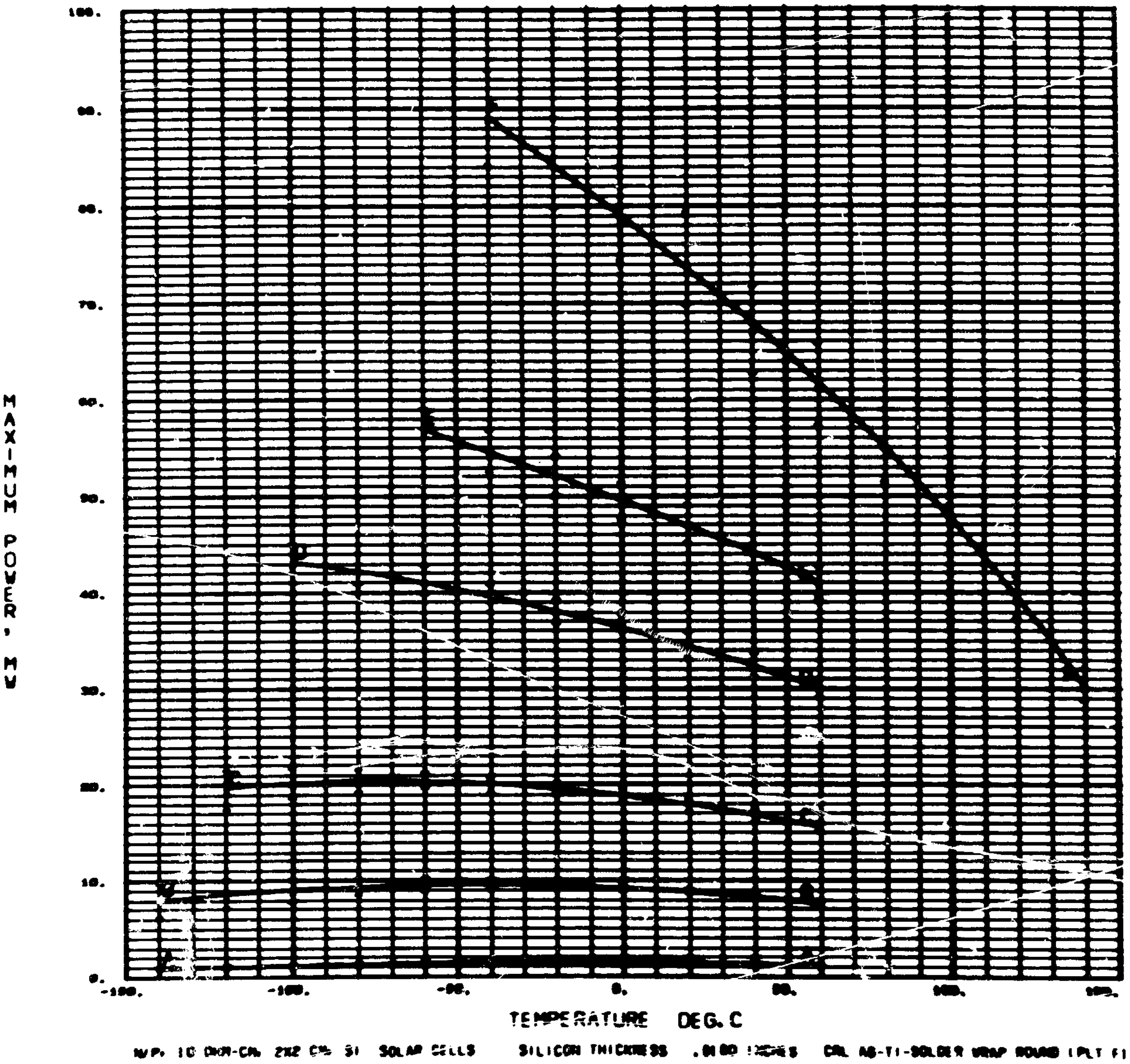
Plate F-1



N/P, 10 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES

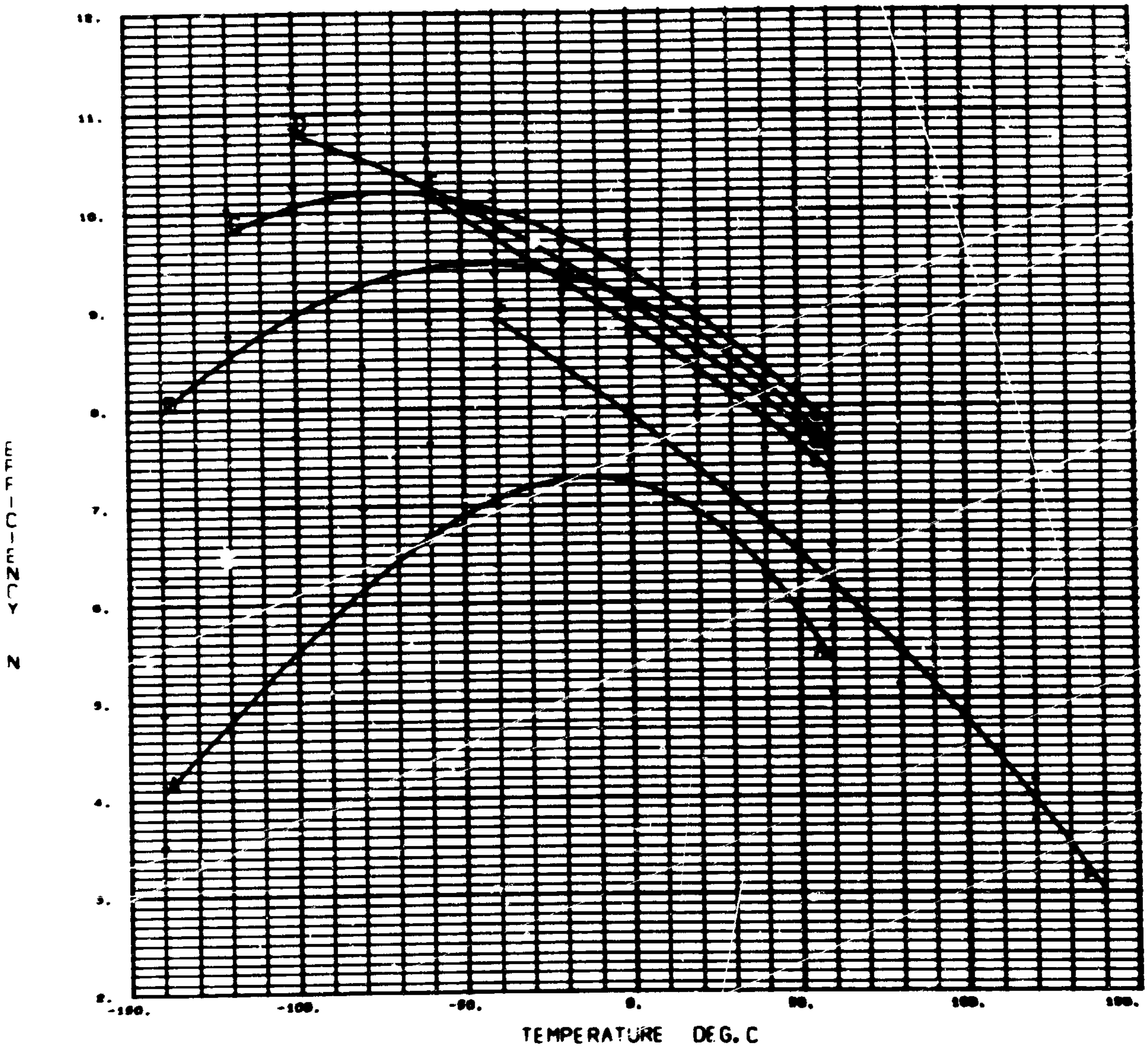
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate F-1



CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

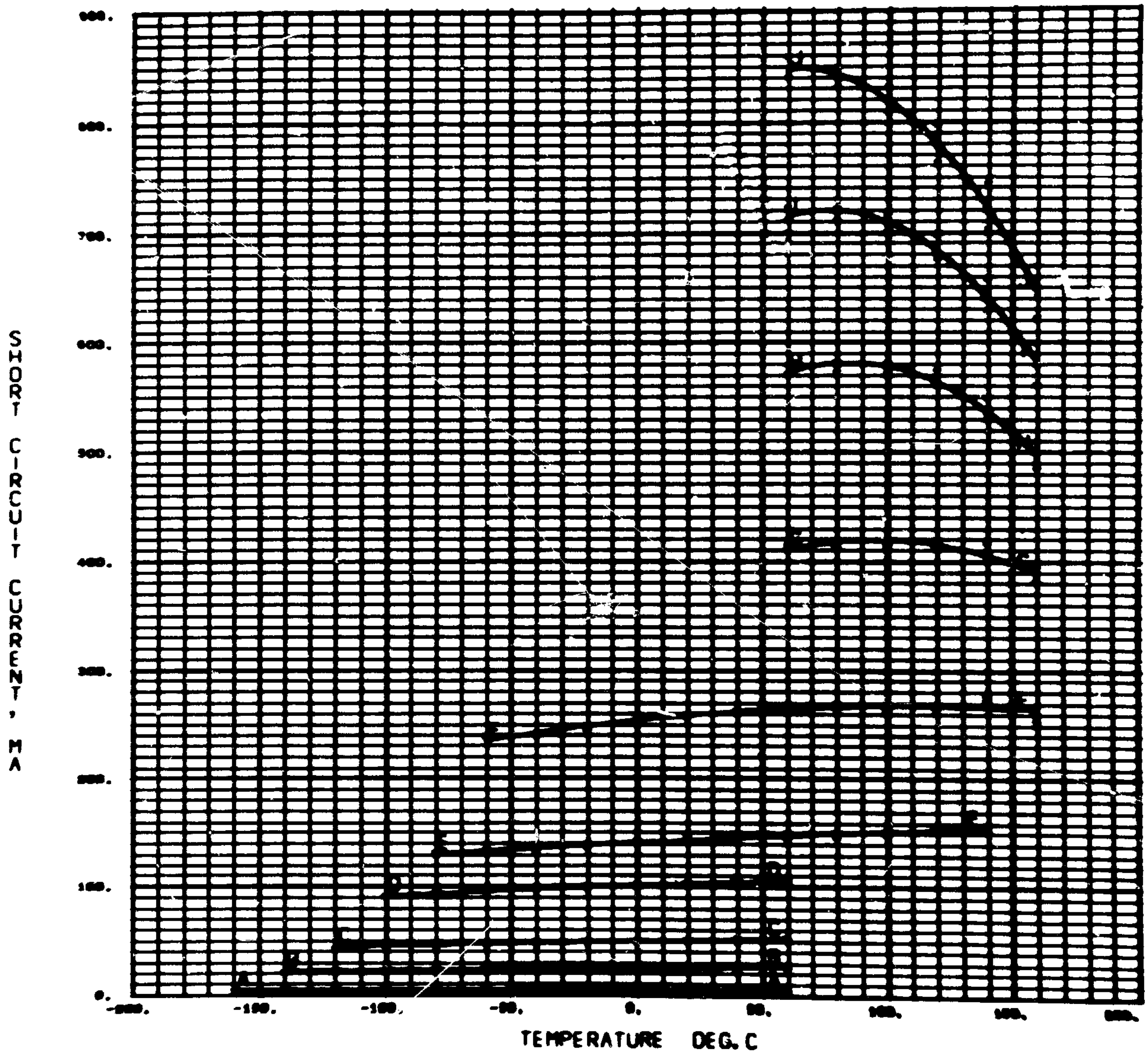
Plate F-1



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-TI-SOLDER WRAP ROUND (PLT F)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

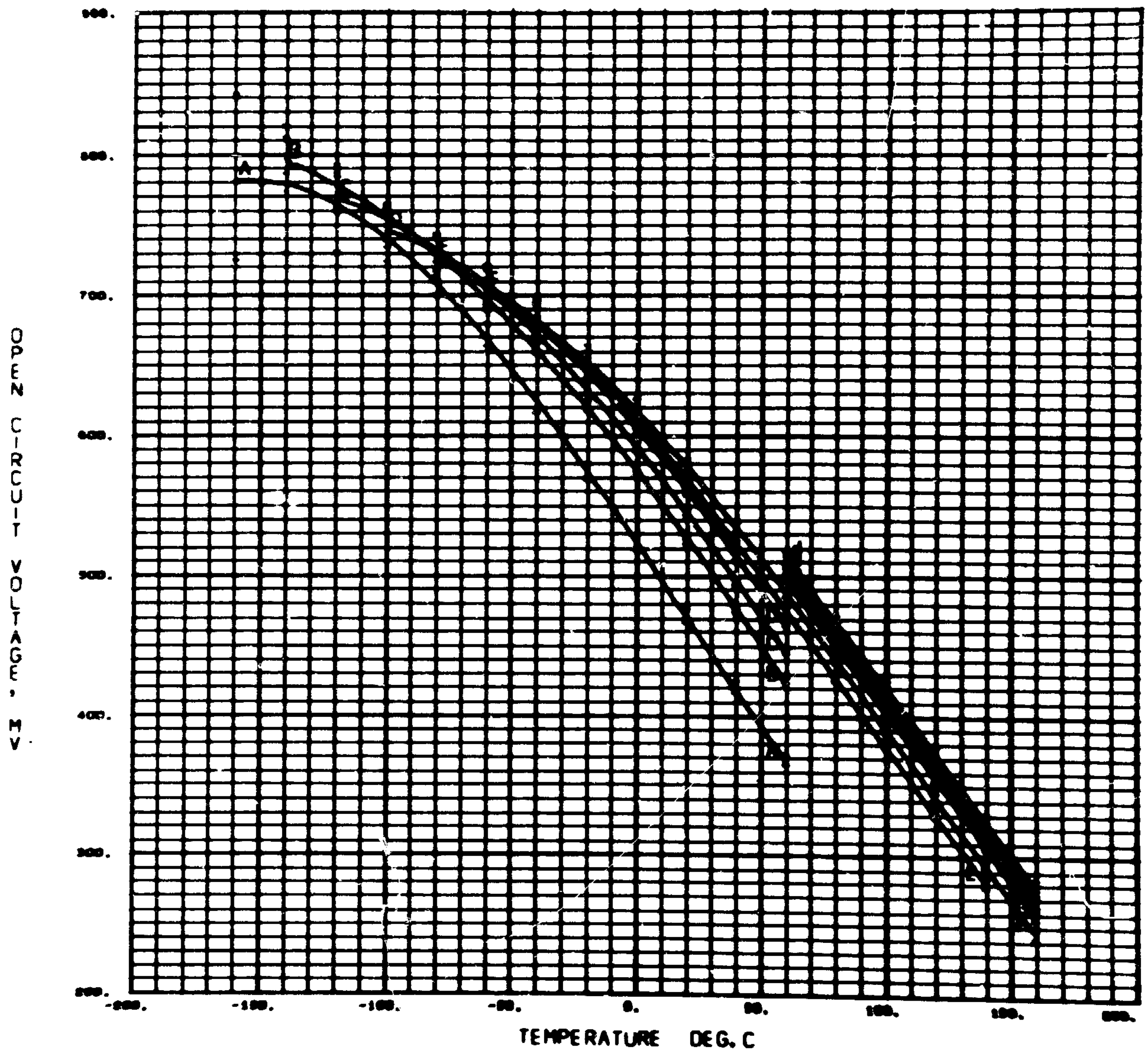
Plate H



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-TI-SOLDER

CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7357	2.857	3.929	5.000	6.0714

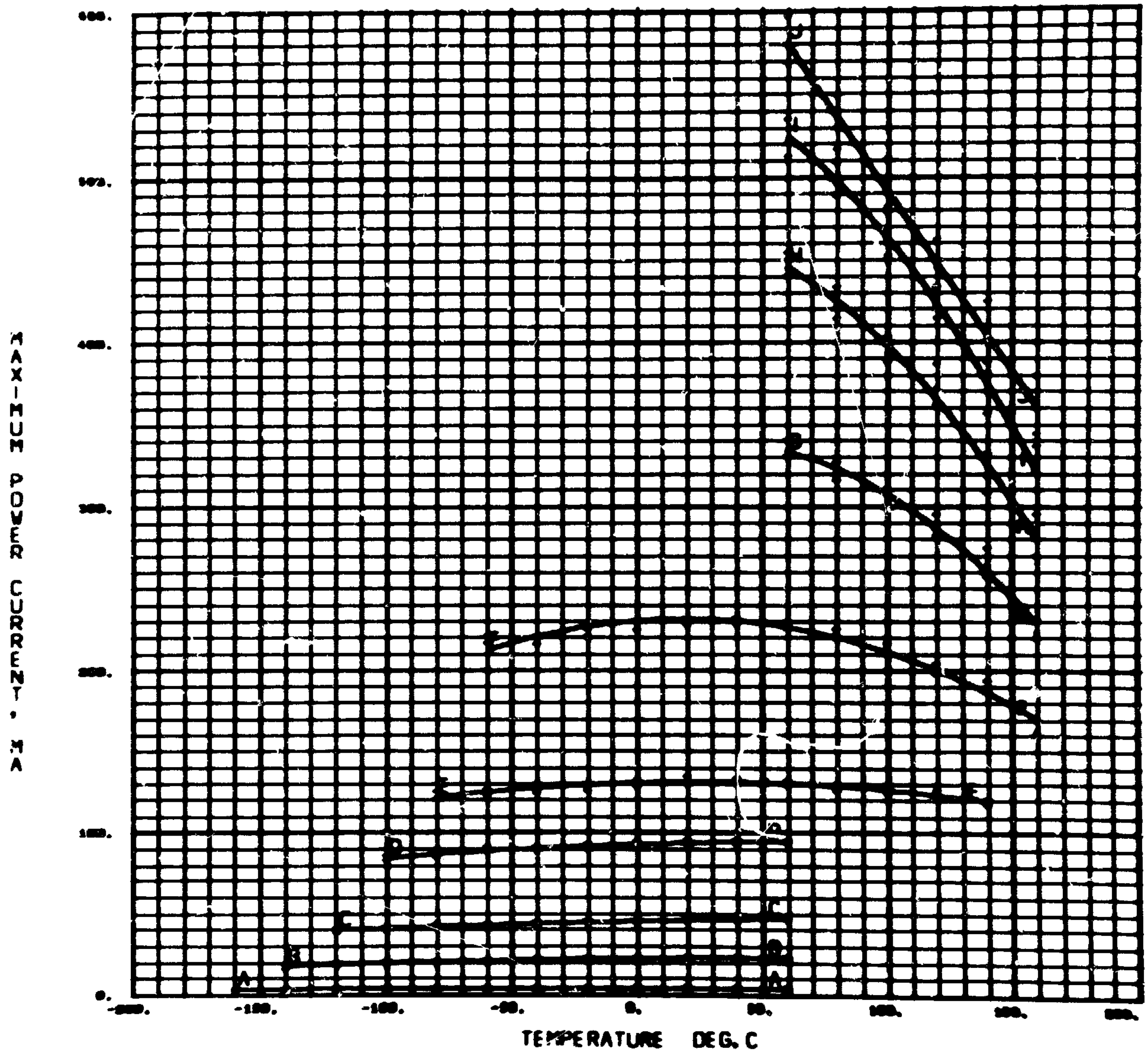
Plate H



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0150 INCHES CRL AG-TI-SOLDER

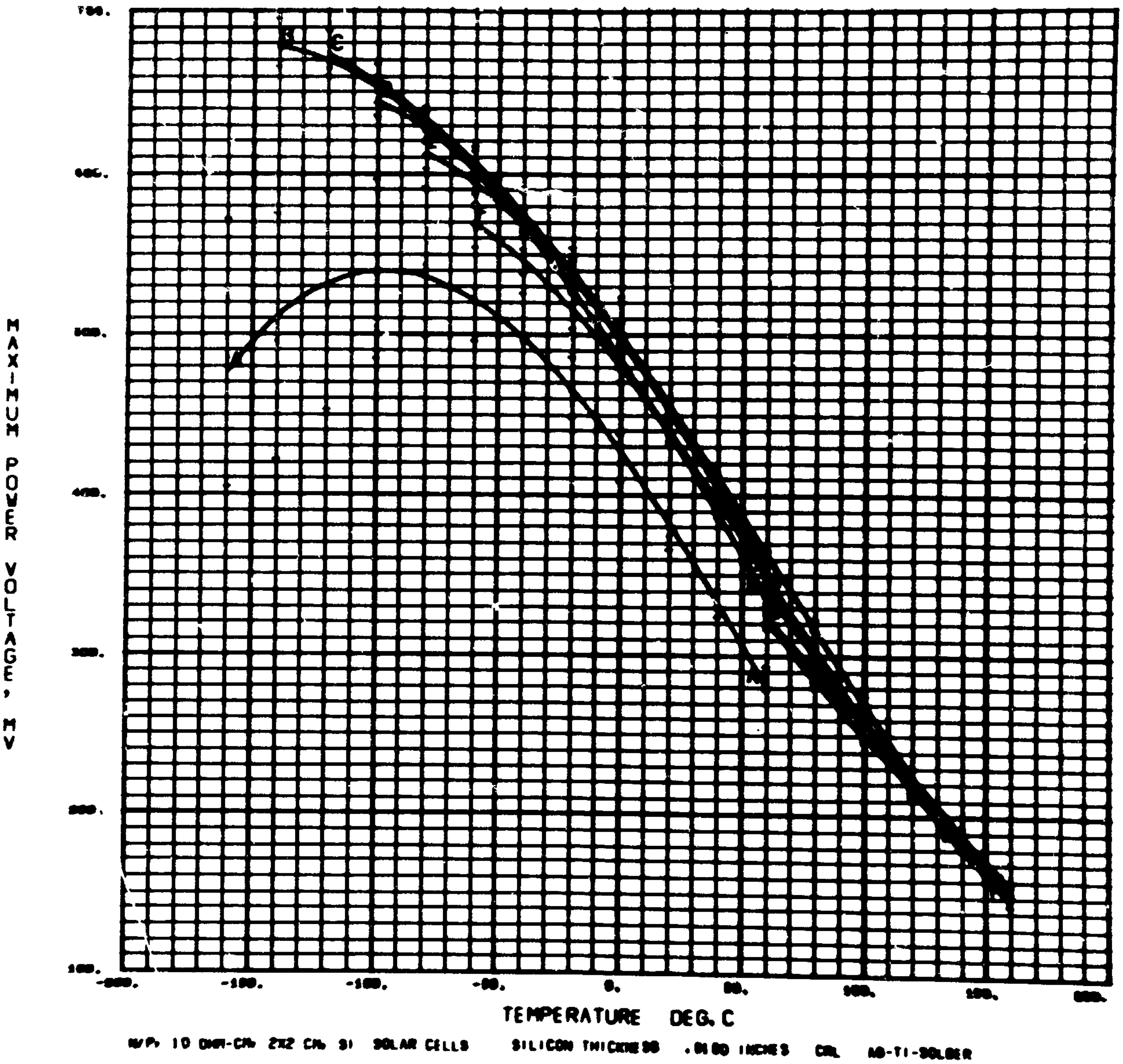
CURVE ID	A	B	C	D	E	F	G	H	i	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

Plate H



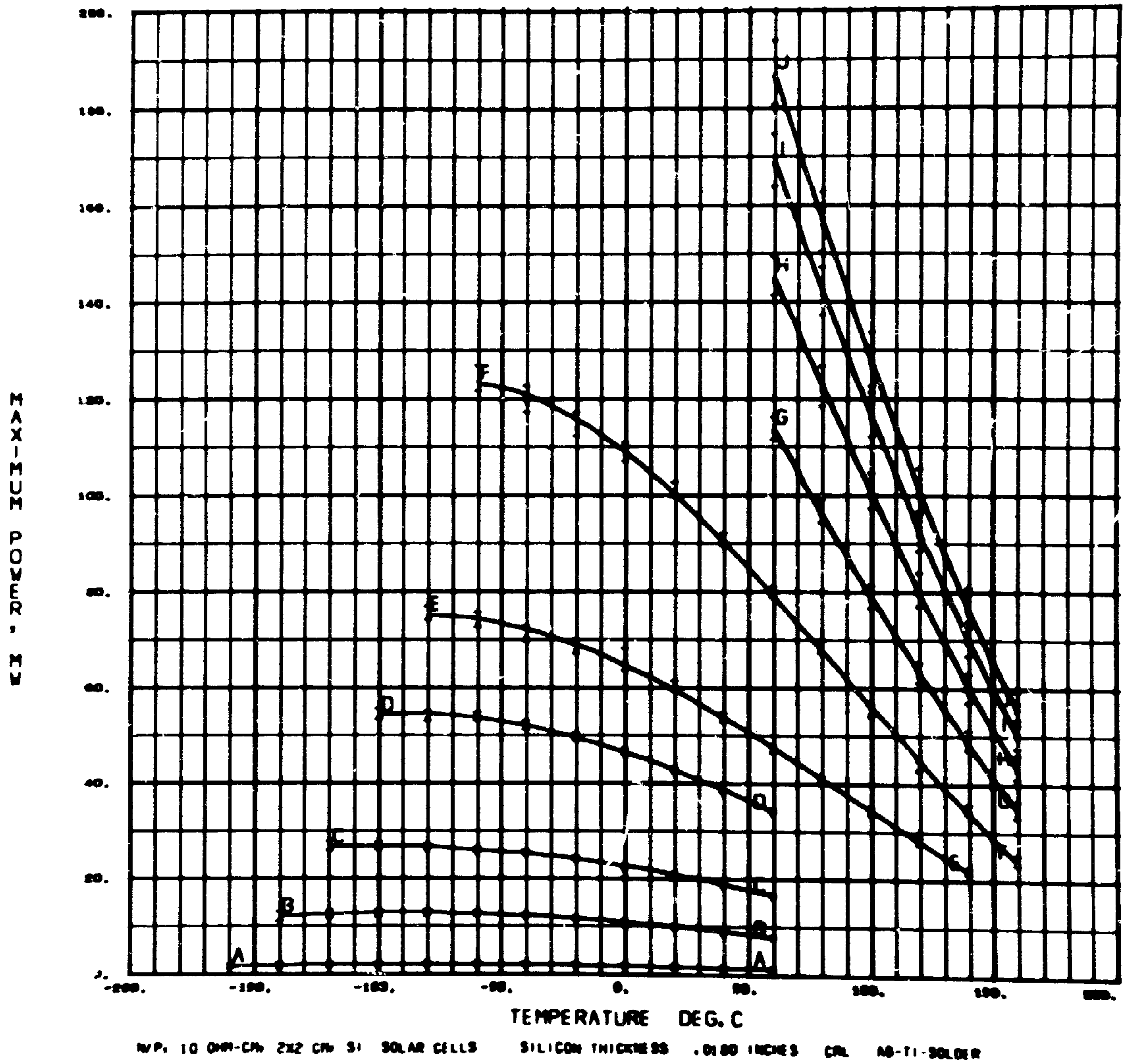
CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

Plate H



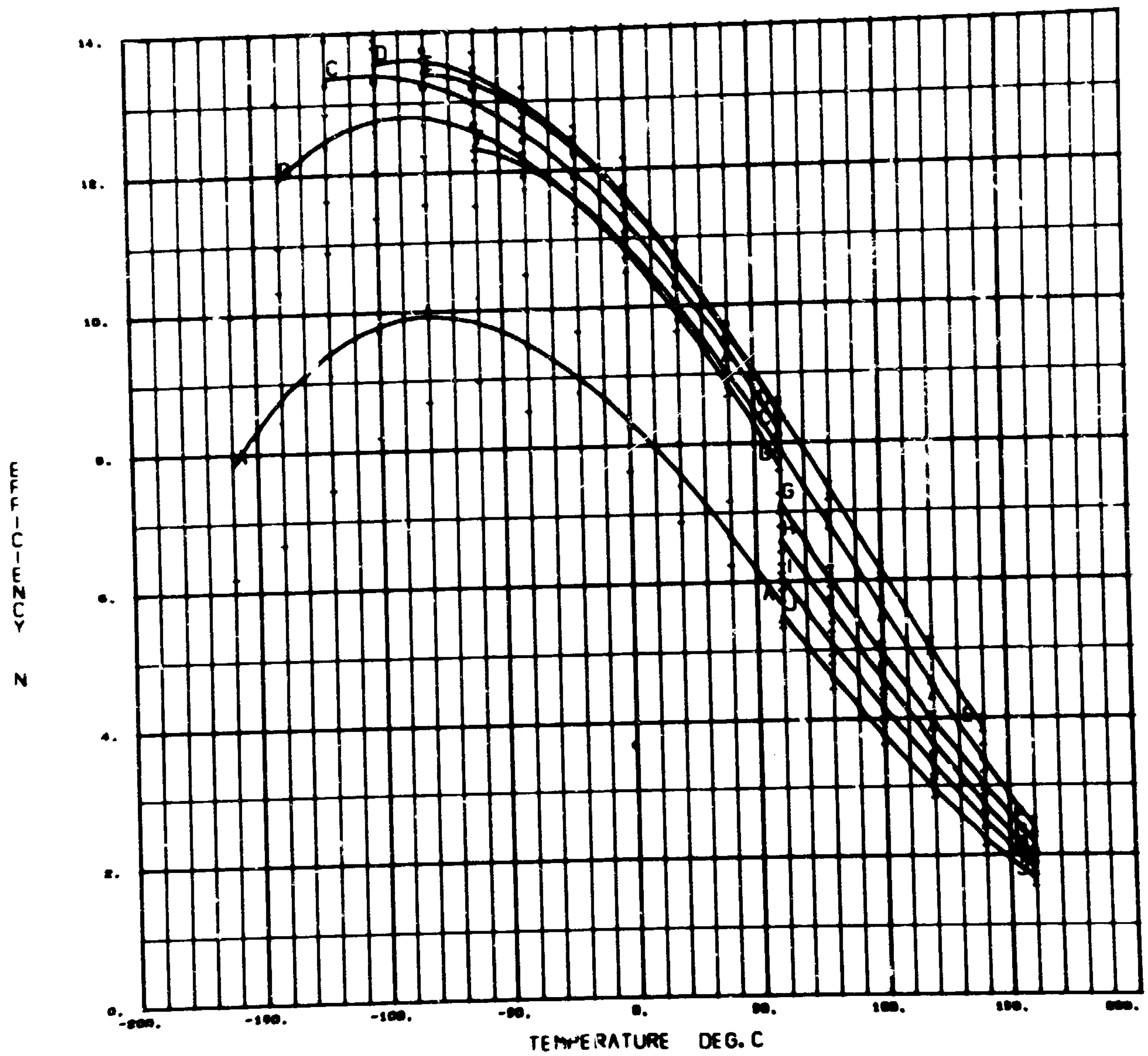
CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

Plate H



CURVE ID	A	B	C	D	E	F	G	H	I	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

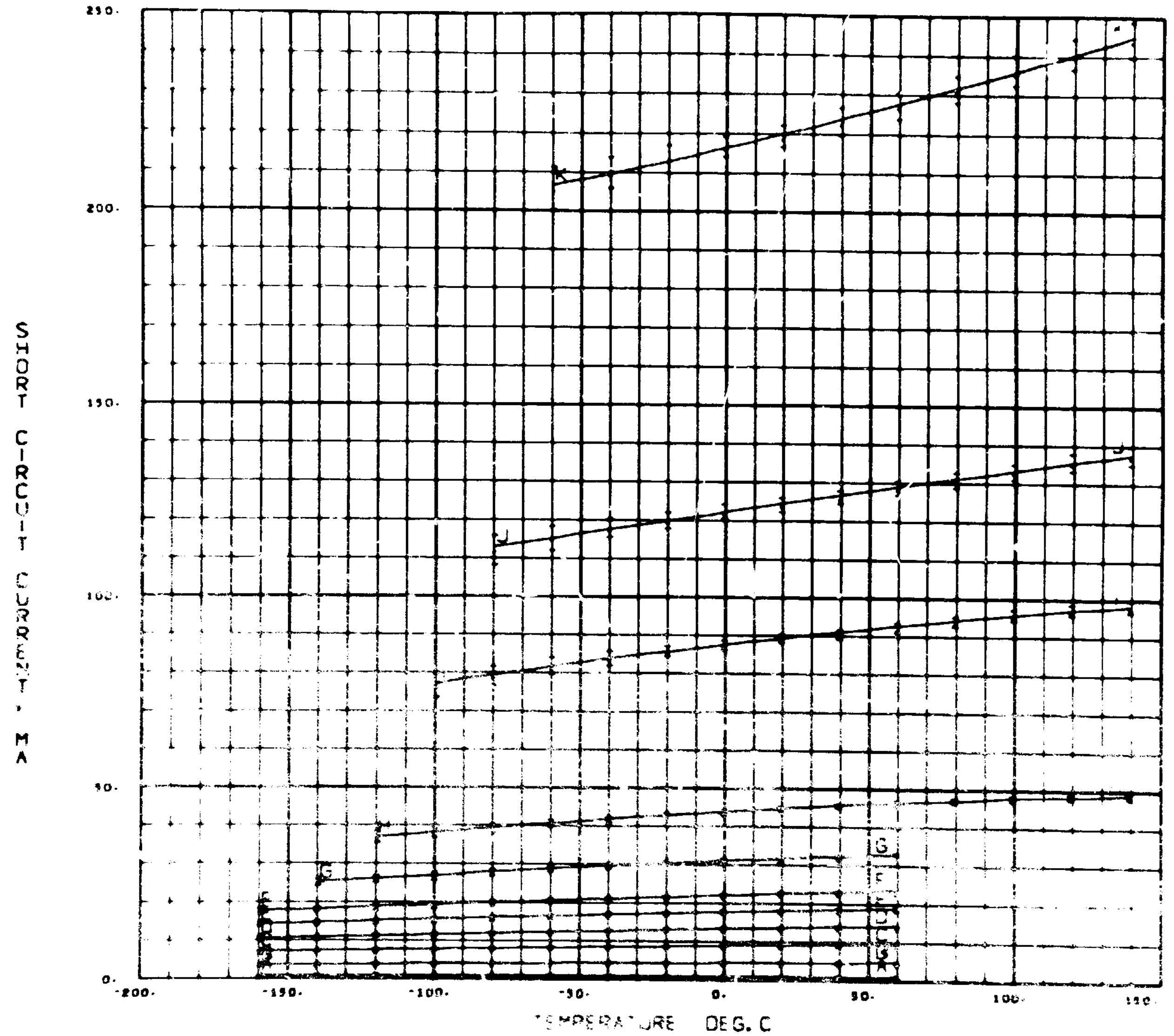
Plate H



N/P 10 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0180 INCHES CRL AG-TI-SOLDER

CURVE ID	A	B	C	D	E	F	G	H	i	J
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.178	0.3571	0.7143	1.000	1.7857	2.857	3.929	5.000	6.0714

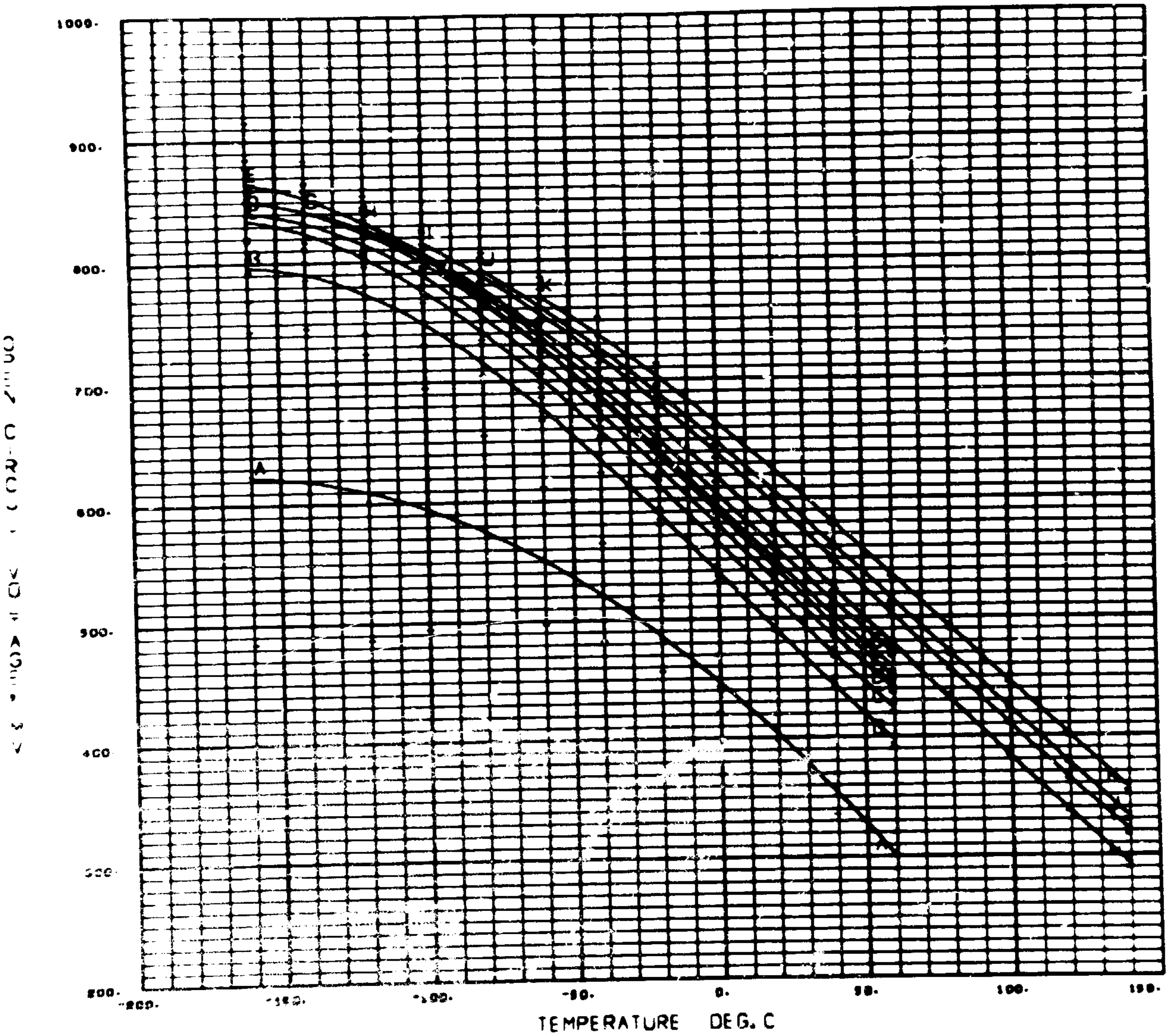
Plate J(a)



N/P, 2 OHM CM, 2X2 CM, SIL SOLAR CELLS SILICON THICKNESS .0140 INCHES [illegible]

CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.2857

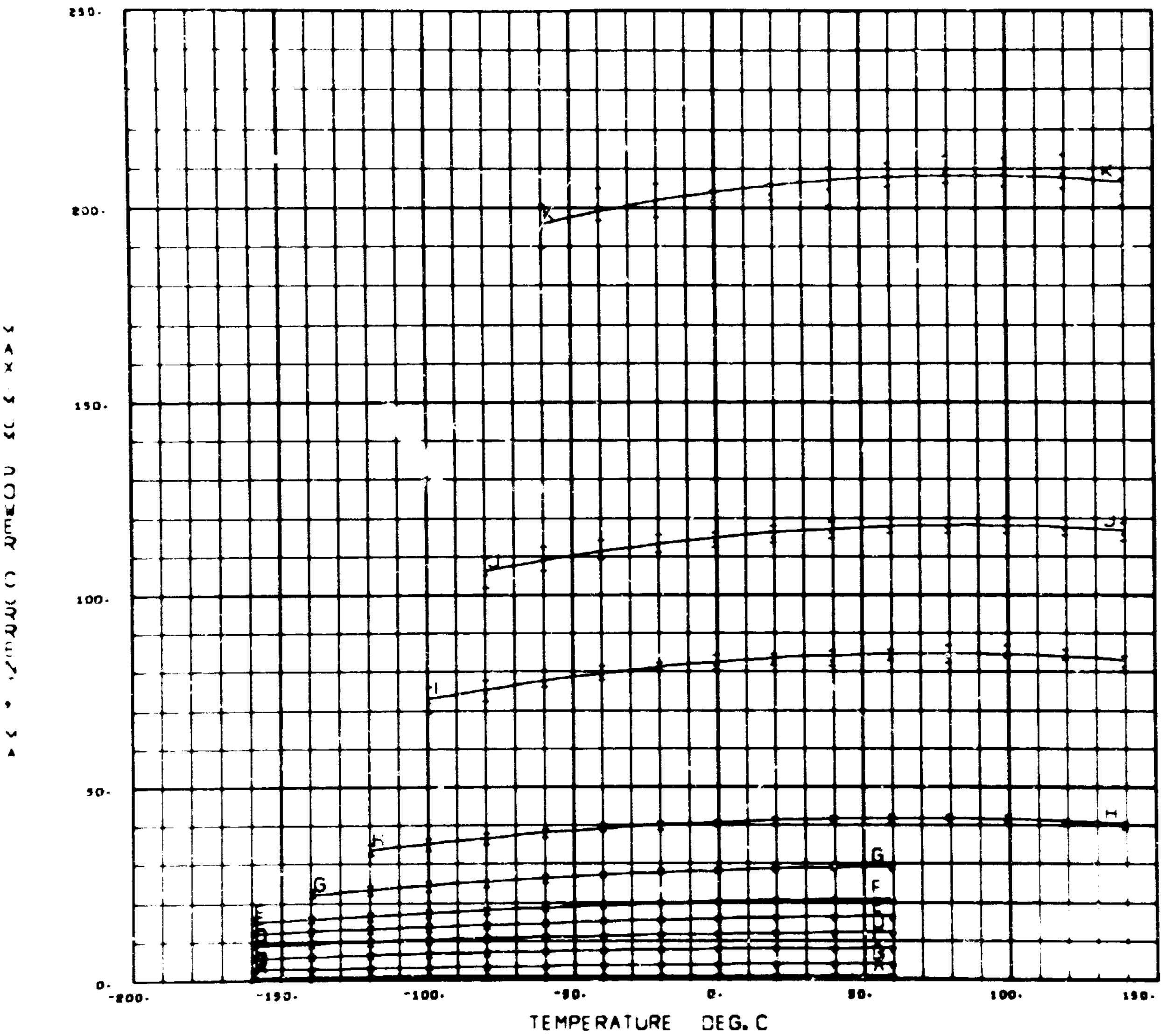
Plate J(a)



N/P 2 OHM-CM 2X2 CM SIL SOLAR CELLS SILICON THICKNESS .0140 INCHES H&K AG-TI-SOLDER (PLATE J)

CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

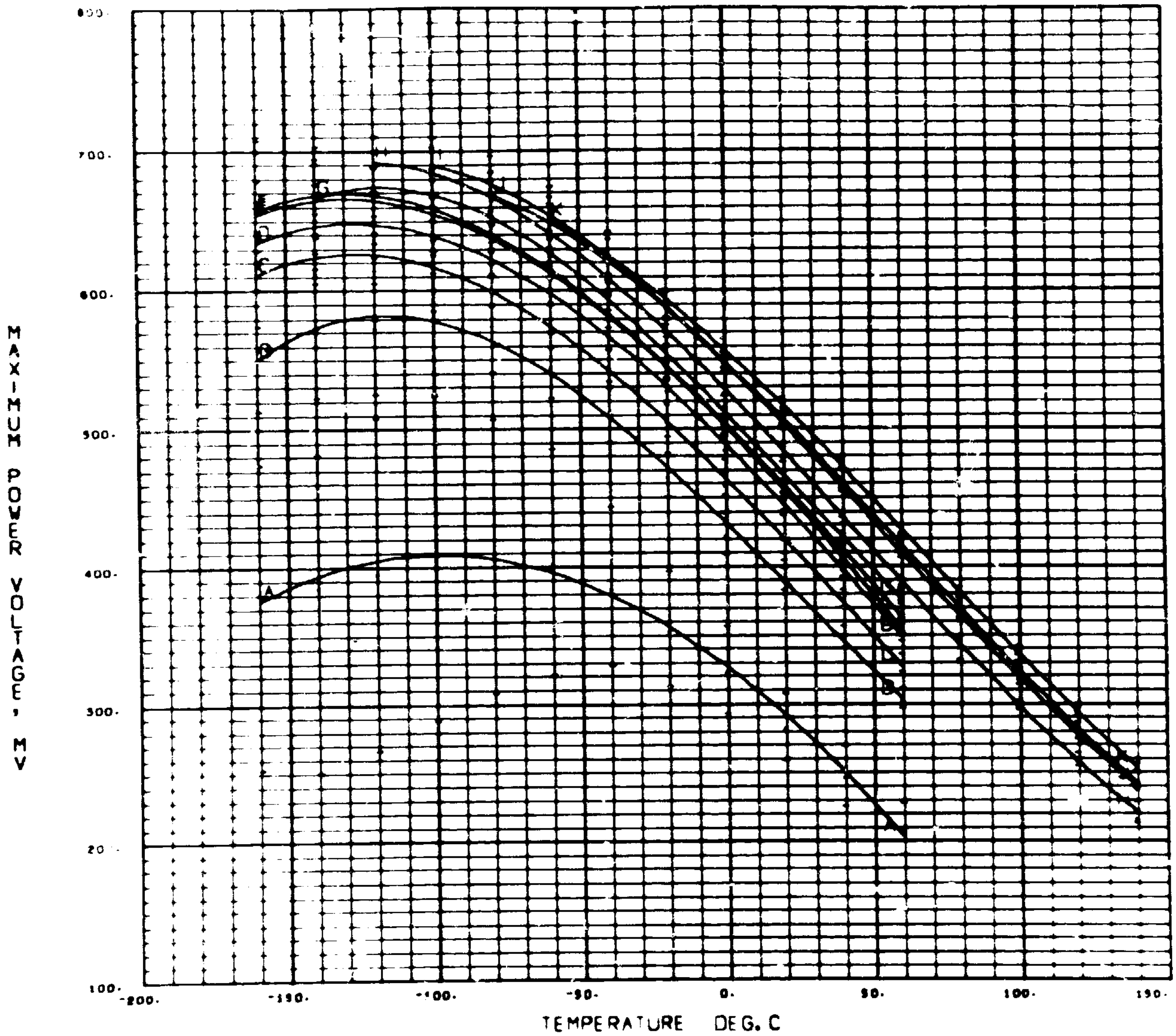
Plate J(a)



N/P 2 OHM-CM 2X2 CM SIL SOLAR CELLS SILICON THICKNESS .0140 INCHES HEX AB-TI-SOLDER (PLATE J)

CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

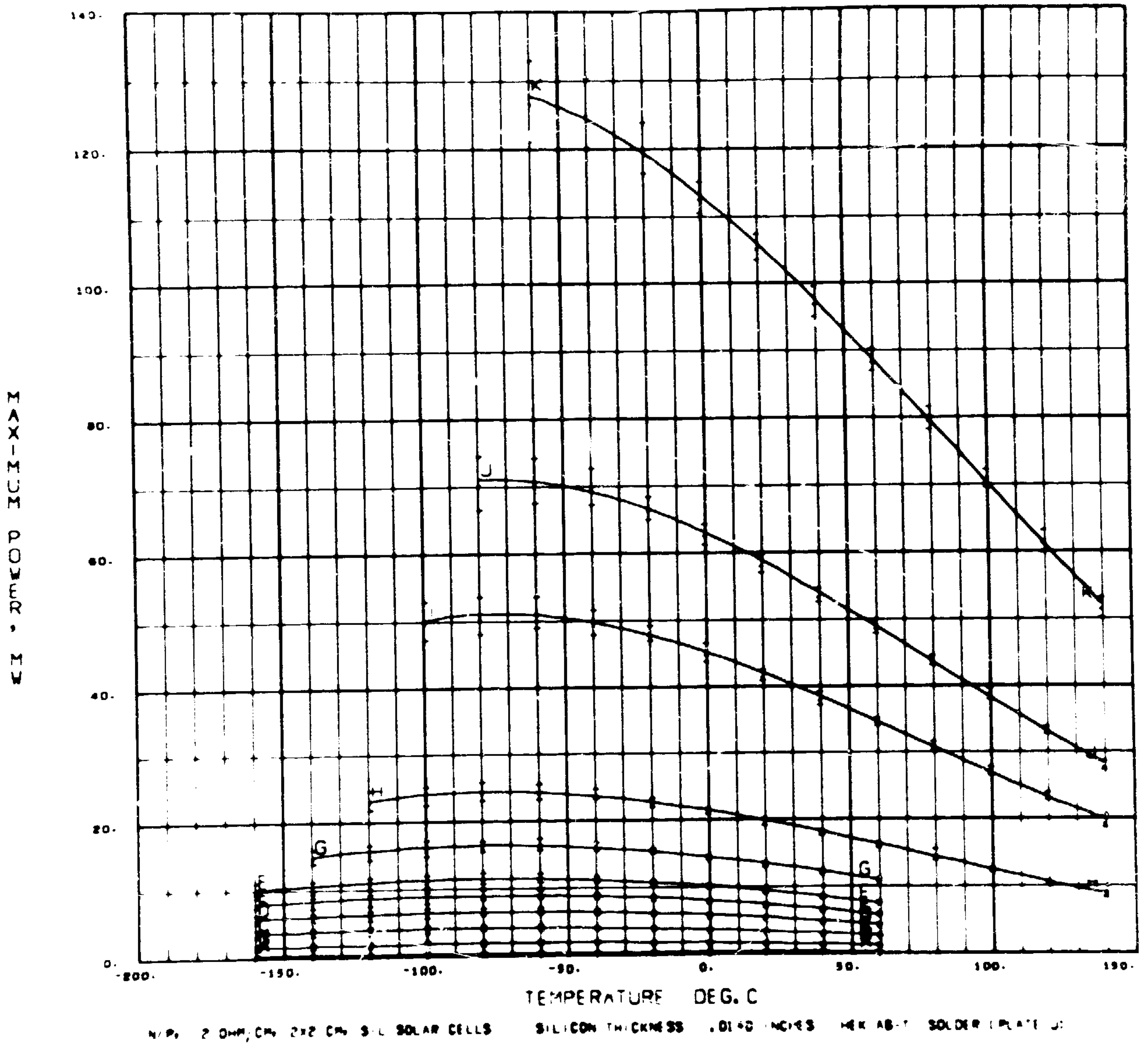
Plate J(a)



2X2 CM SIL SOLAR CELLS SILICON THICKNESS .0140 INCHES

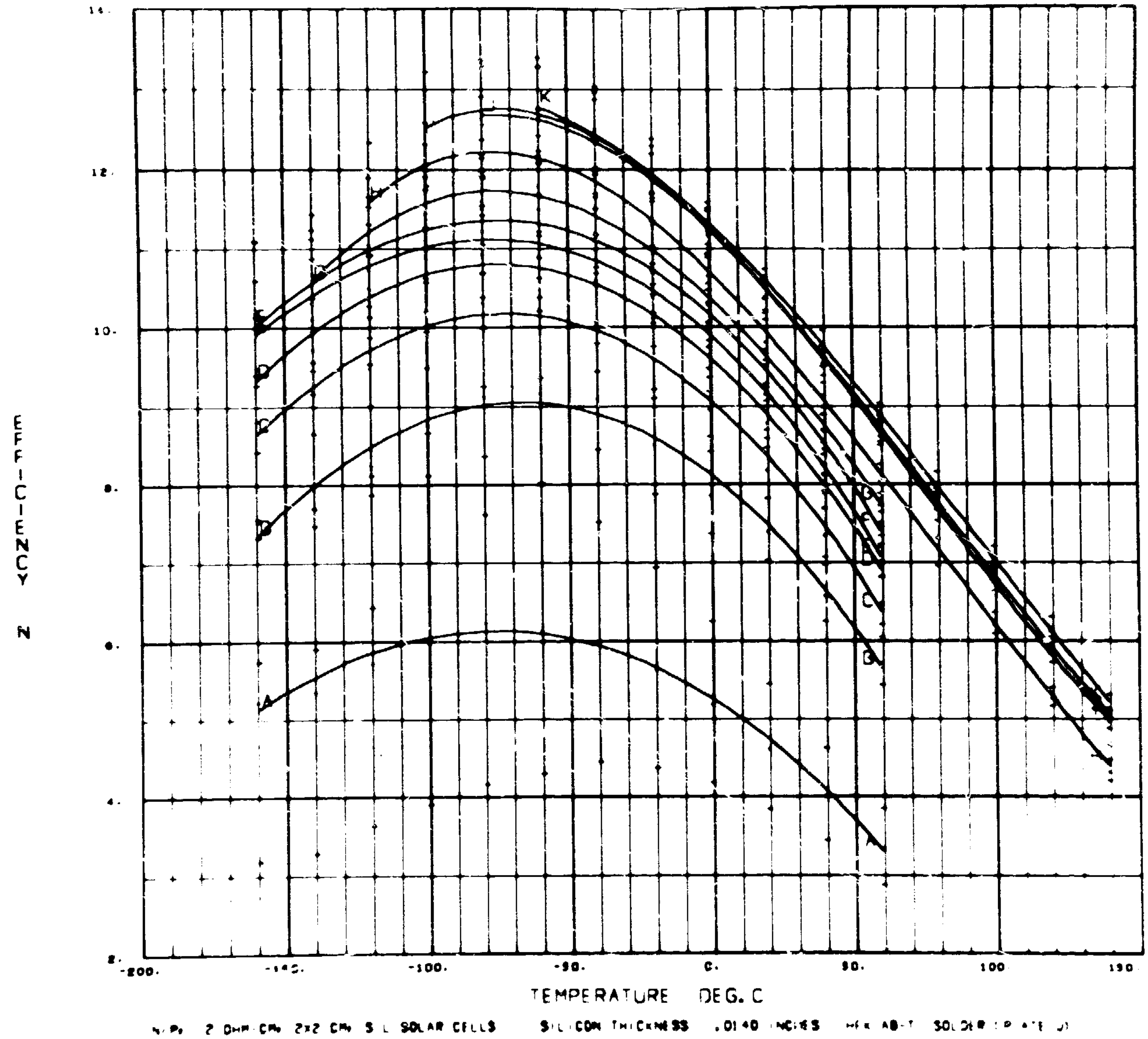
CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

Plate J(a)



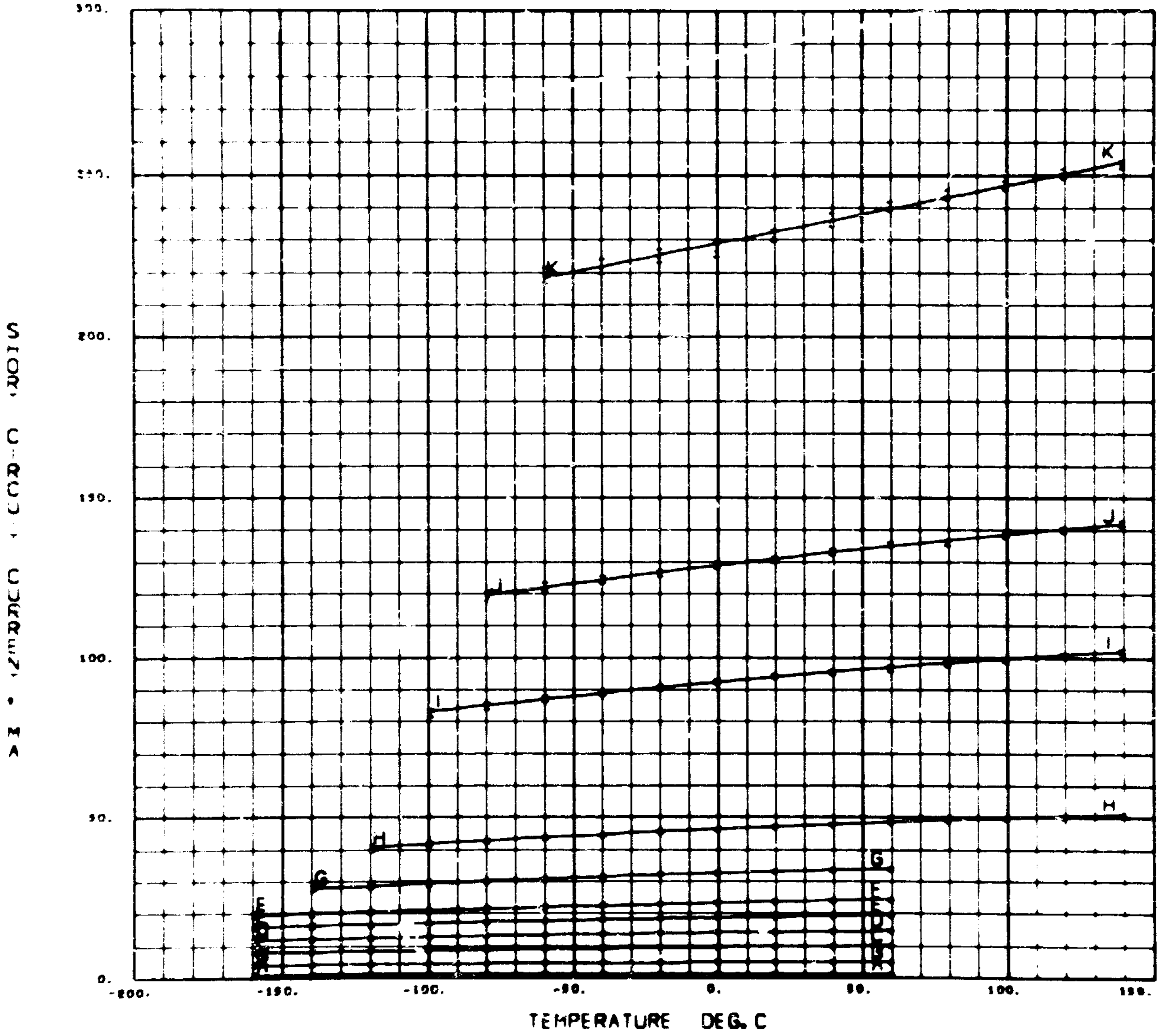
CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

Plate J(a)



CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

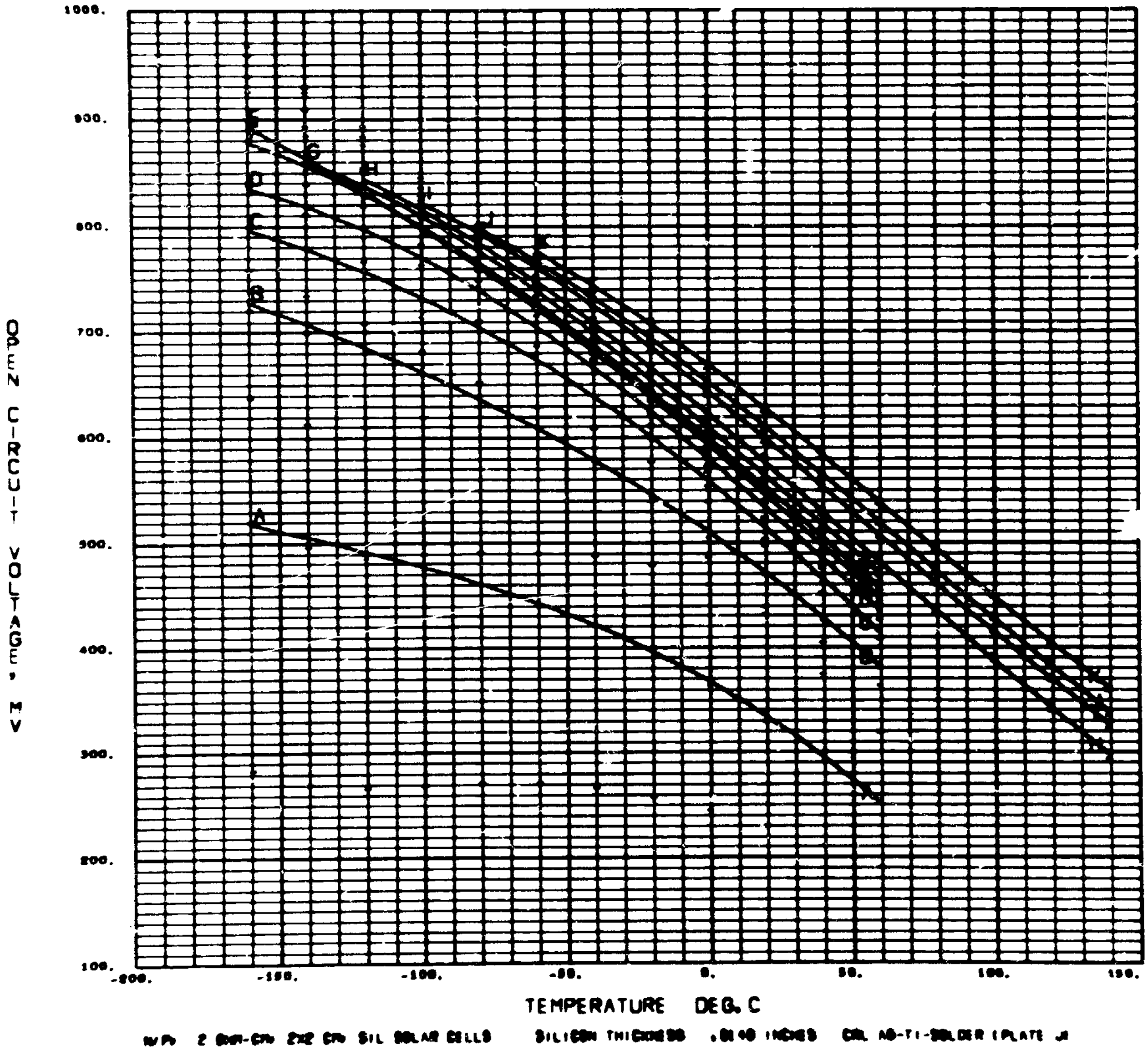
Plate J(b)



N/P 2 OHM-CM 2X2 CM SIL SOLAR CELLS SILICON THICKNESS .0148 INCHES CR. AG-TI-SOLDER (PLATE J)

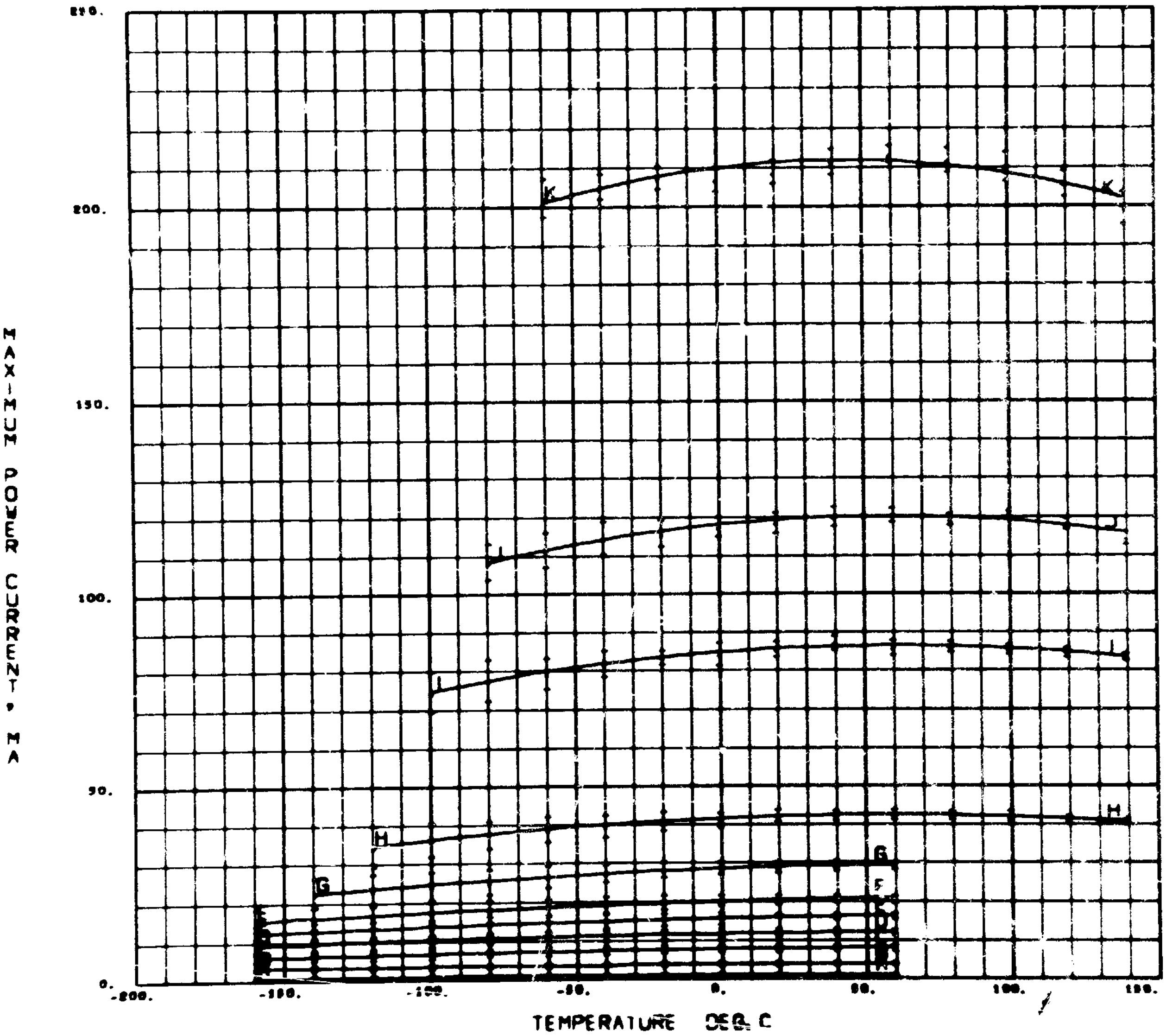
CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

Plate J(b)



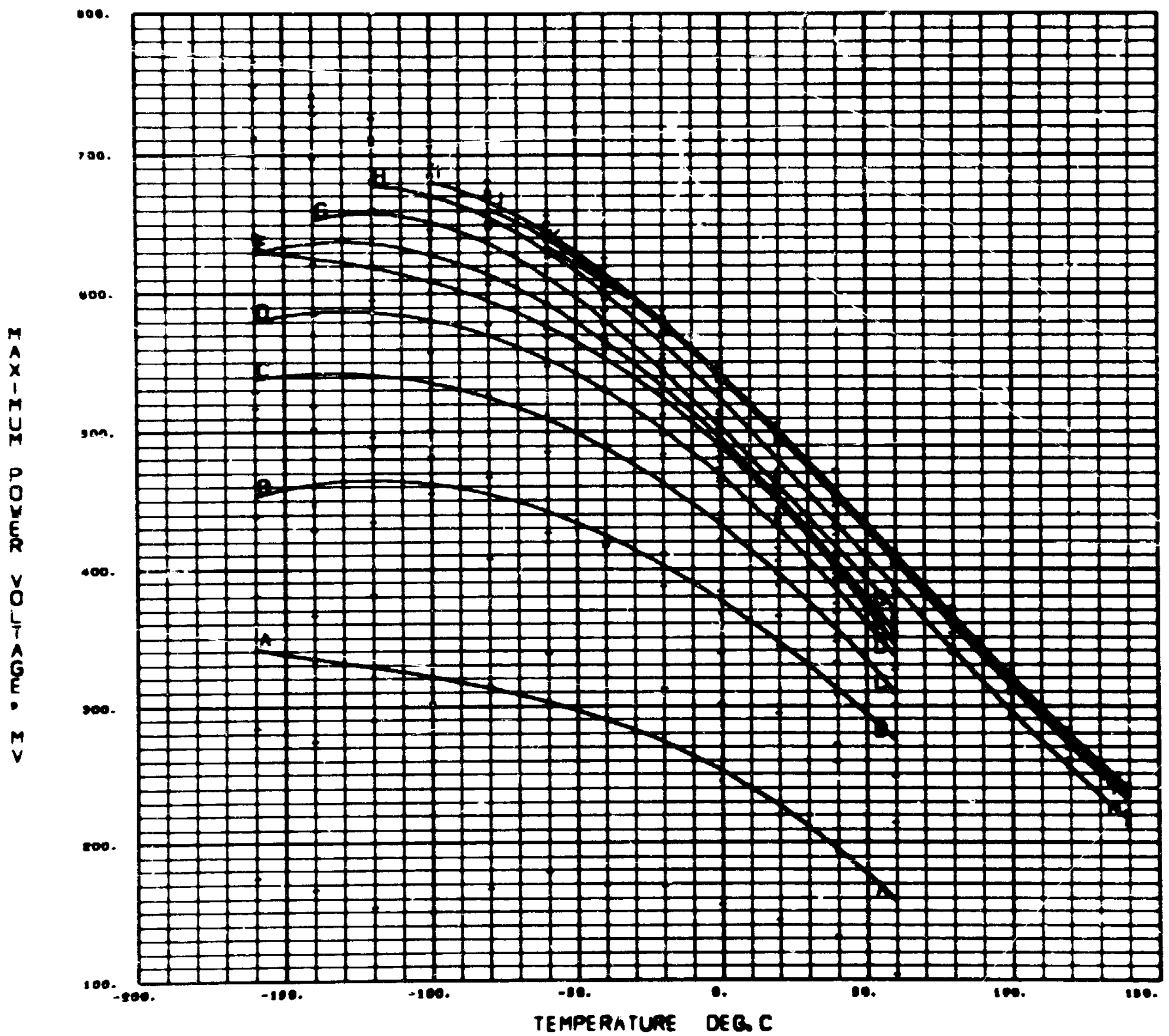
CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

Plate J(b)



CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

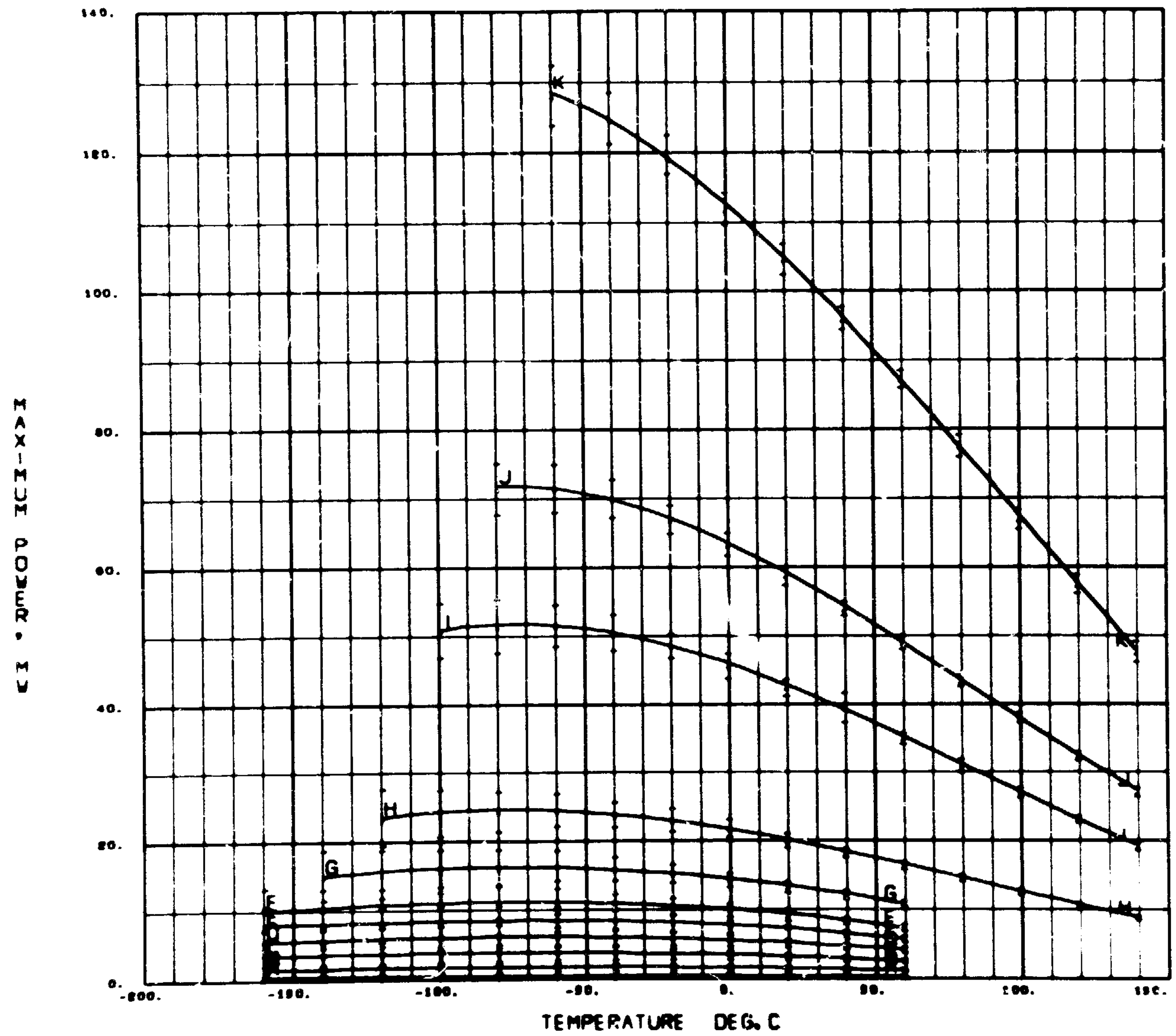
Plate J(b)



2 OHM-CM 2X2 CM SIL SOLAR CELLS SILICON THICKNESS .0140 INCHES CRL AG-TI-SOLDER (PLATE J)

CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

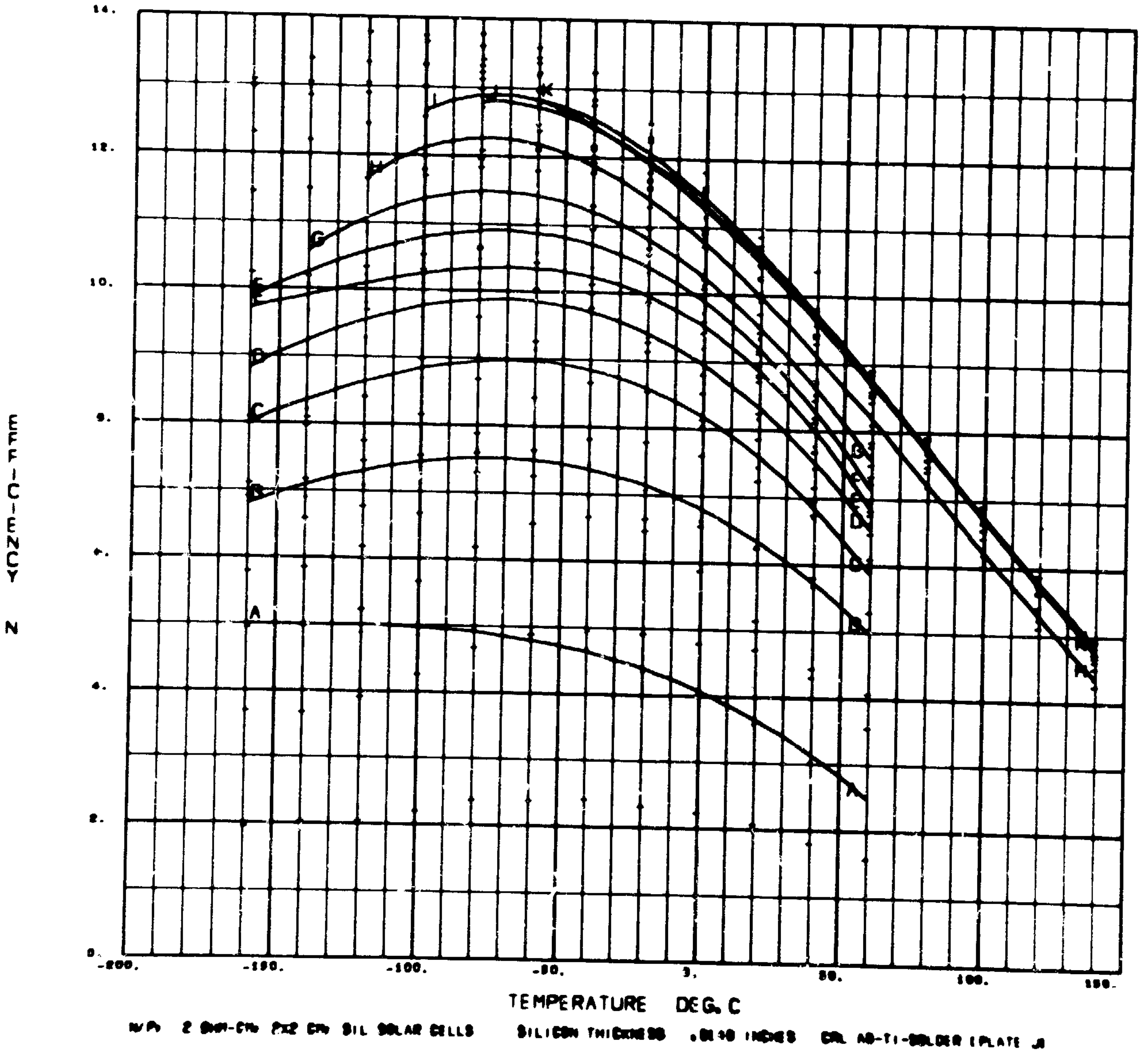
Plate J(b)



N/P 2 OHM-CM 2X2 CM SIL SOLAR CELLS SILICON THICKNESS .0140 INCHES CRL AG-TI-SOLDER (PLATE J)

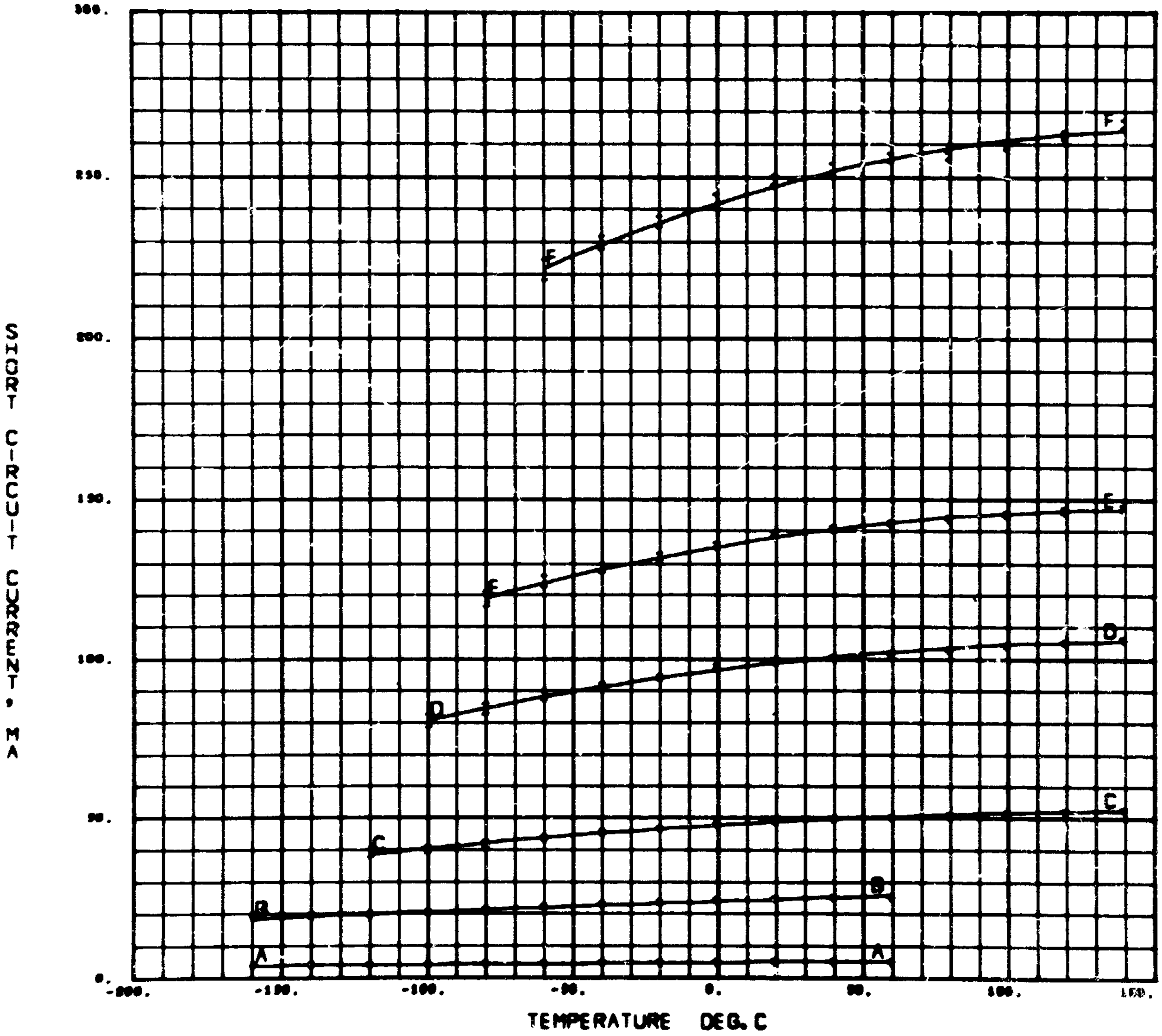
CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

Plate J(b)



CURVE ID	A	B	C	D	E	F	G	H	I	J	K
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0071	0.0357	0.0714	0.1071	0.1429	0.1786	0.250	0.3571	0.7143	1.000	1.7857

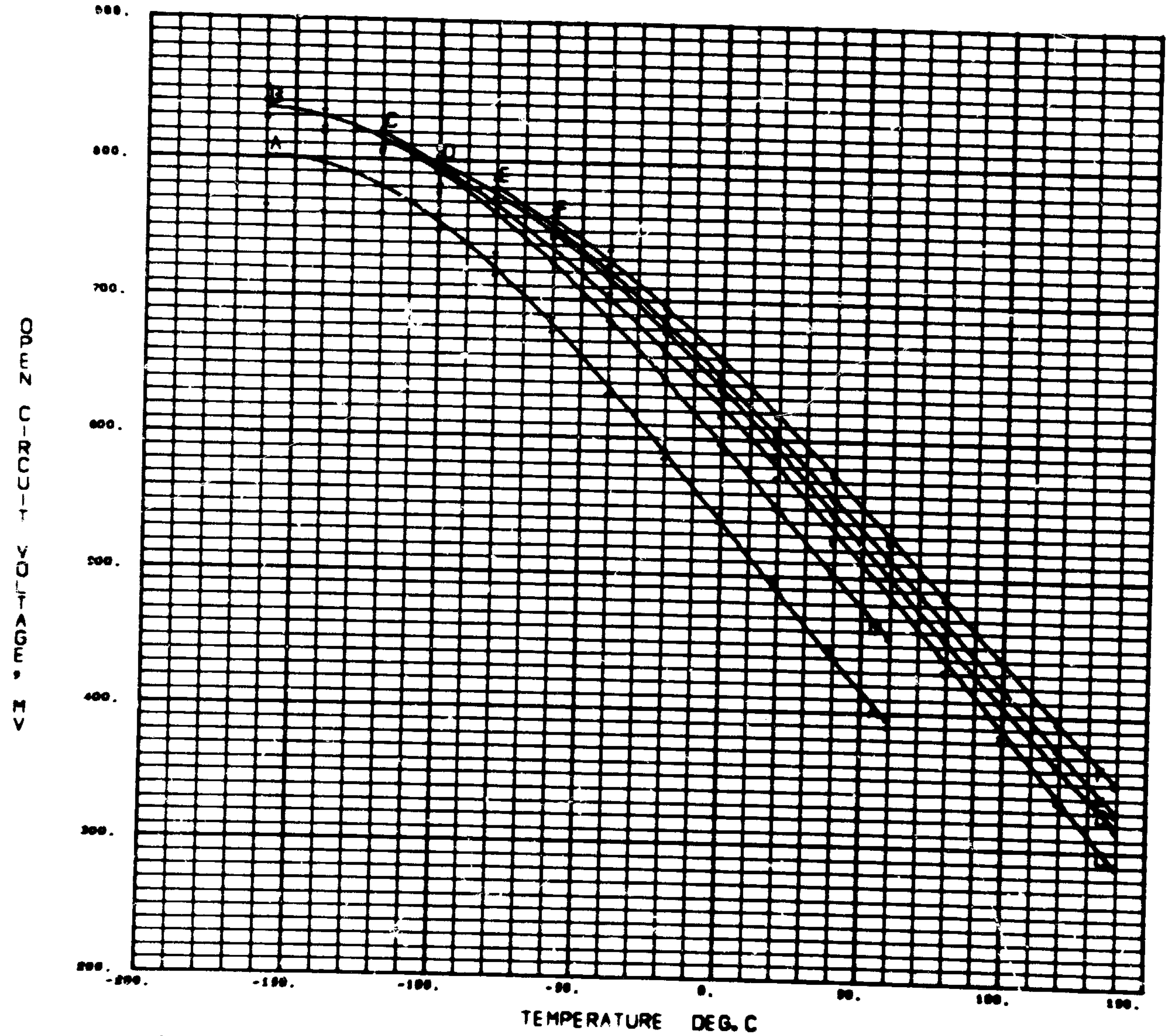
Plate M



N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0140 INCHES

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

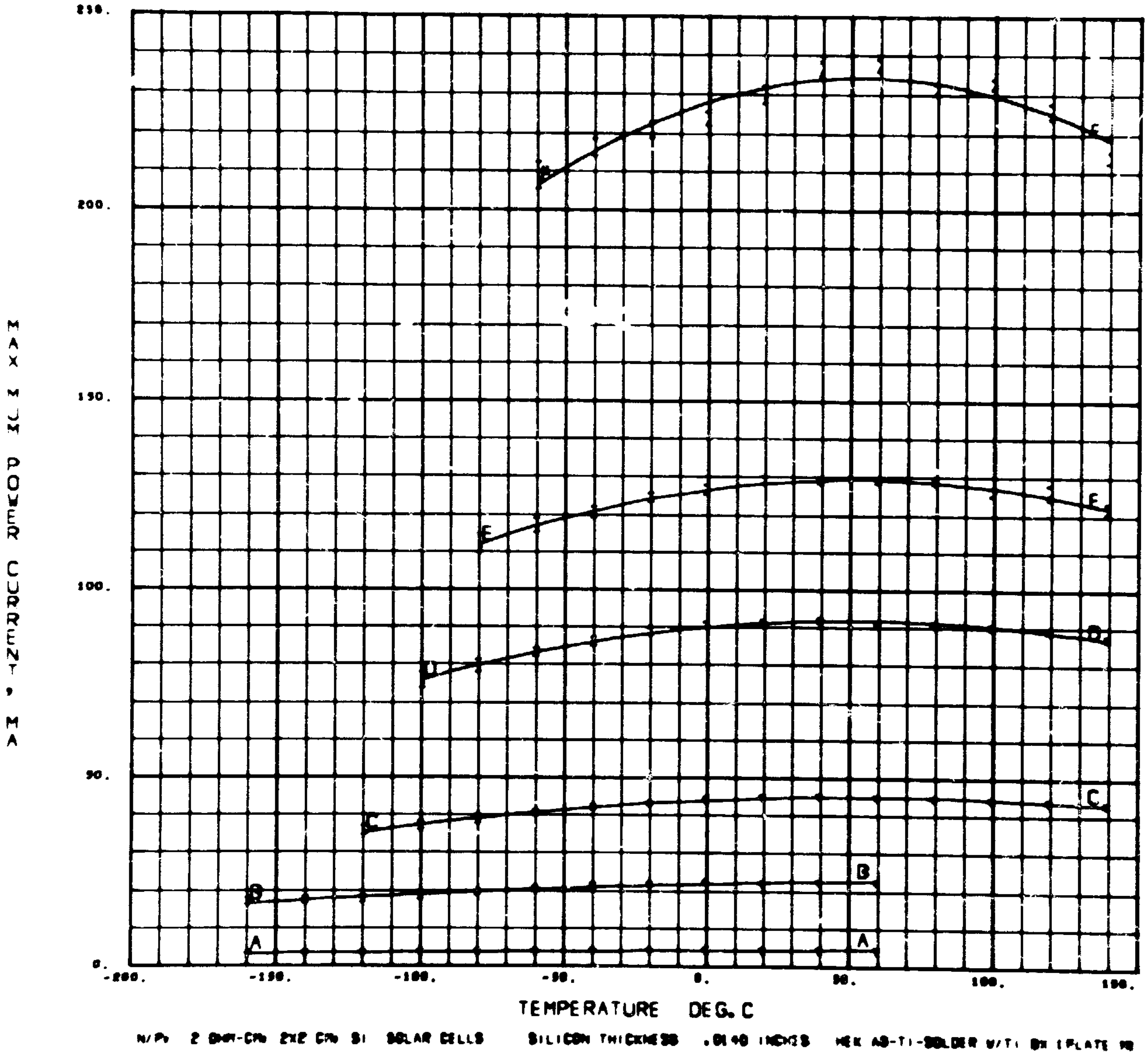
Plate M



N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0140 INCHES HEK AG-TI-SOLDER W/TI 5X (PLATE M)

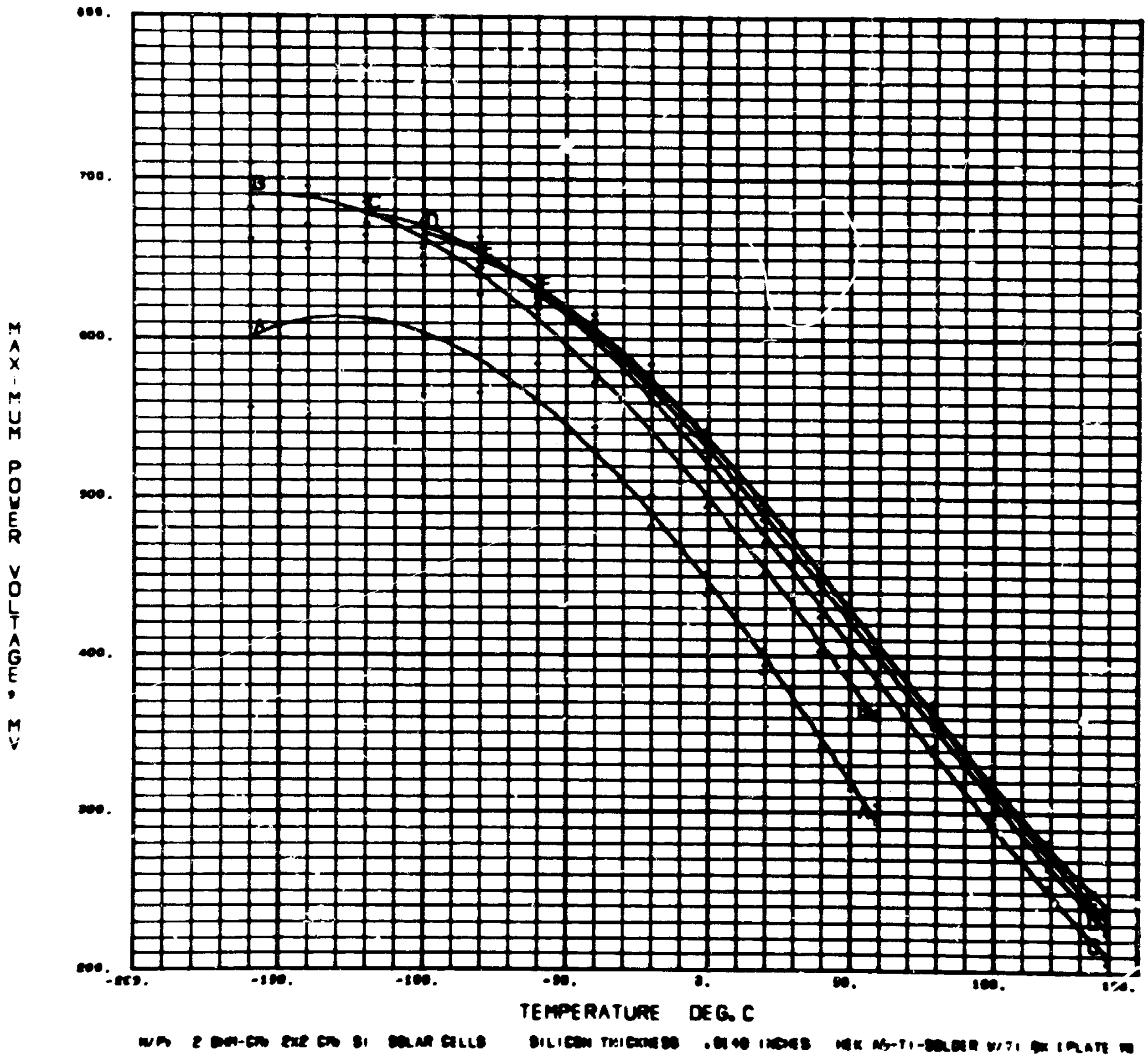
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate M



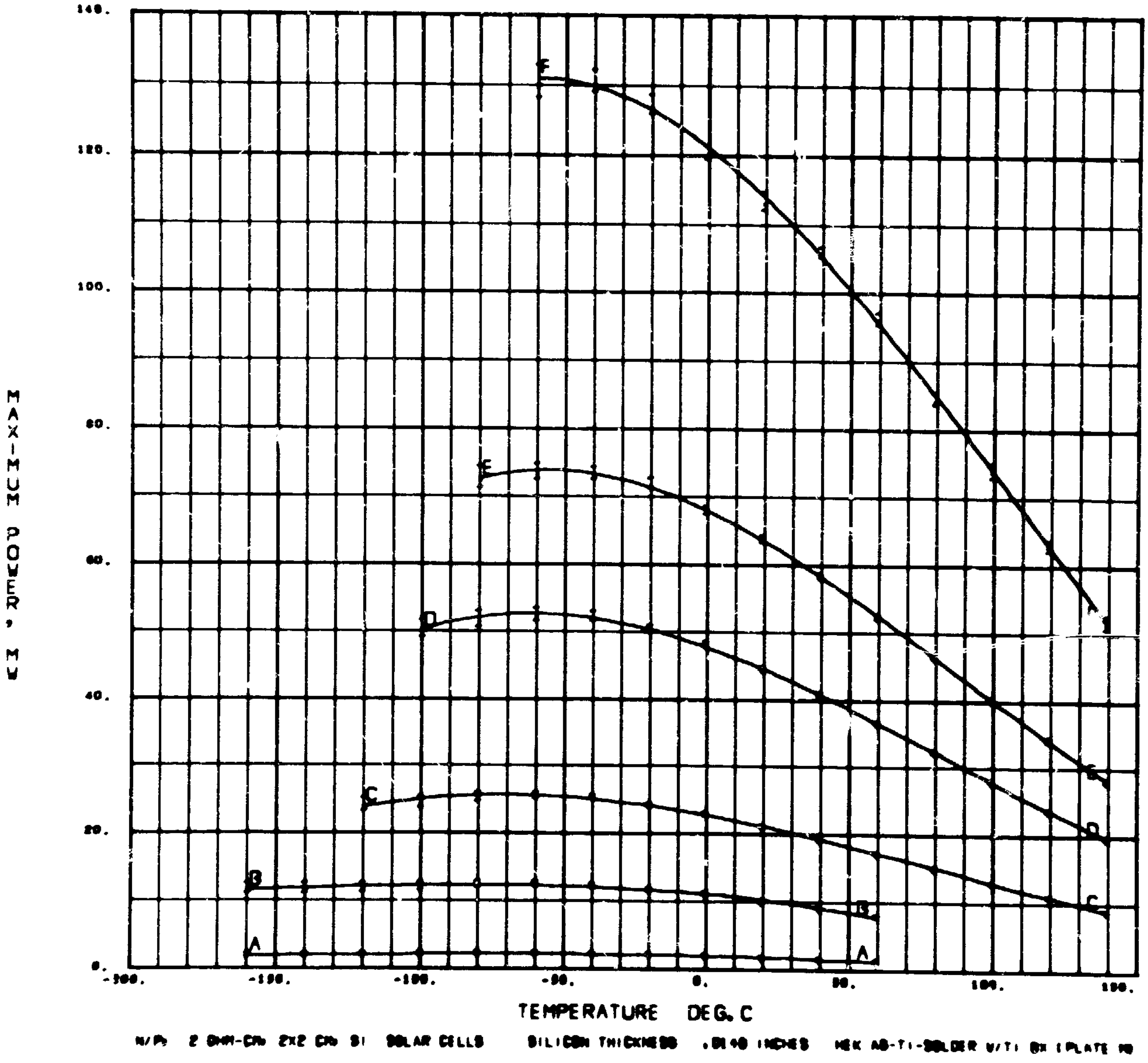
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate M



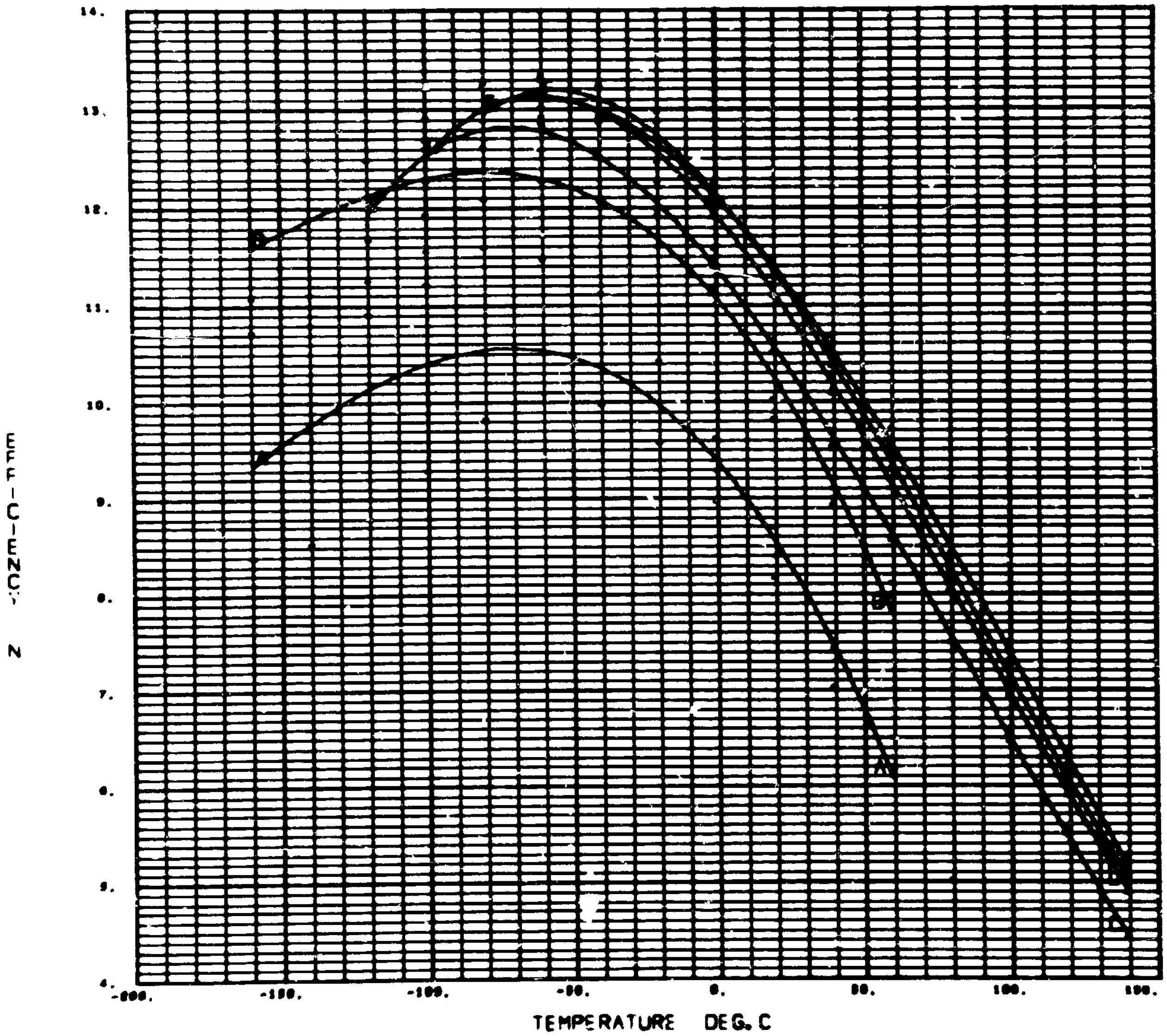
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate M



CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

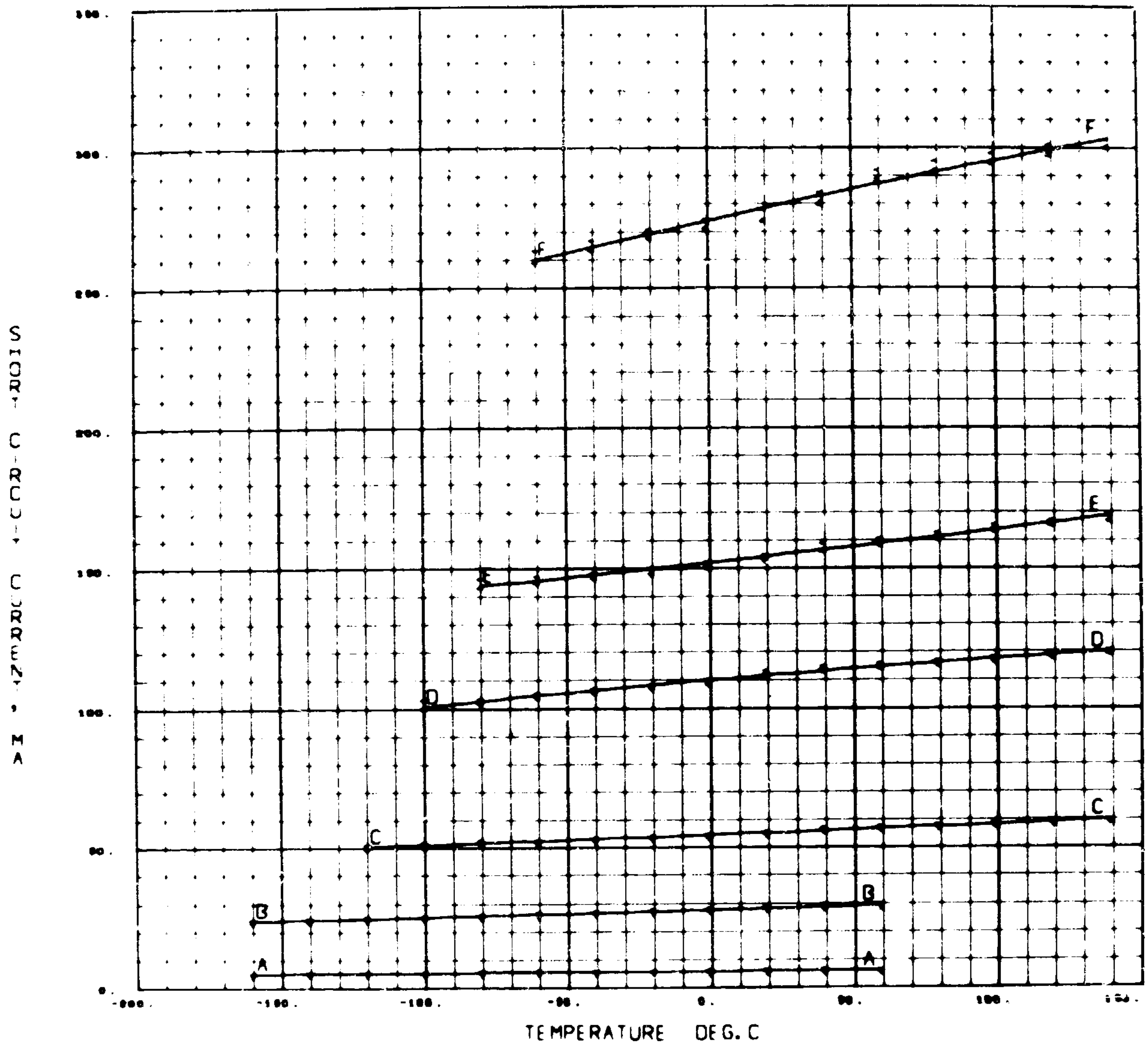
Plate M



N/P 2 OHM-CM 2X2 CM SI SOLAR CELLS SILICON THICKNESS [illegible] INCHES HEX AG-TI-SOLDER W/TI [illegible]

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0357	0.1786	0.3571	0.7143	1.000	1.7857

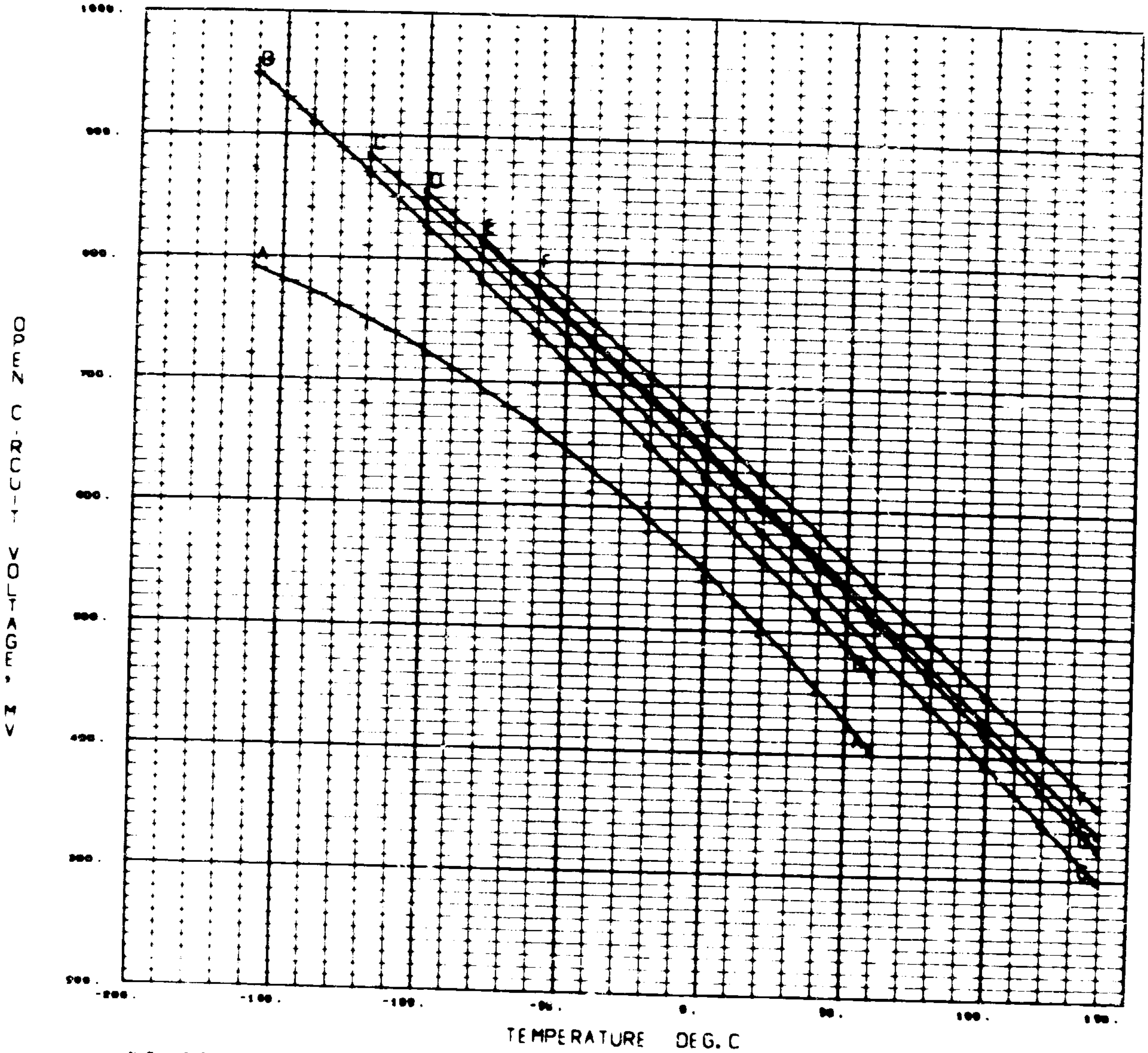
Plate N



N/P, 2 OHM CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES CPL AG-PD-TI SOLDERLESS (PLATE N)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate N

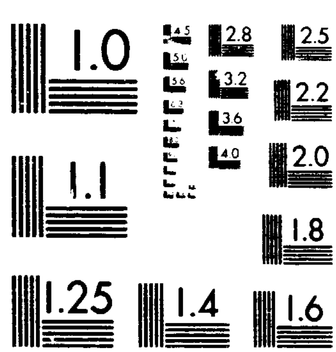


N P, 2 OHM CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES CRL AG-PD TI SOLDERLESS (PLATE N)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

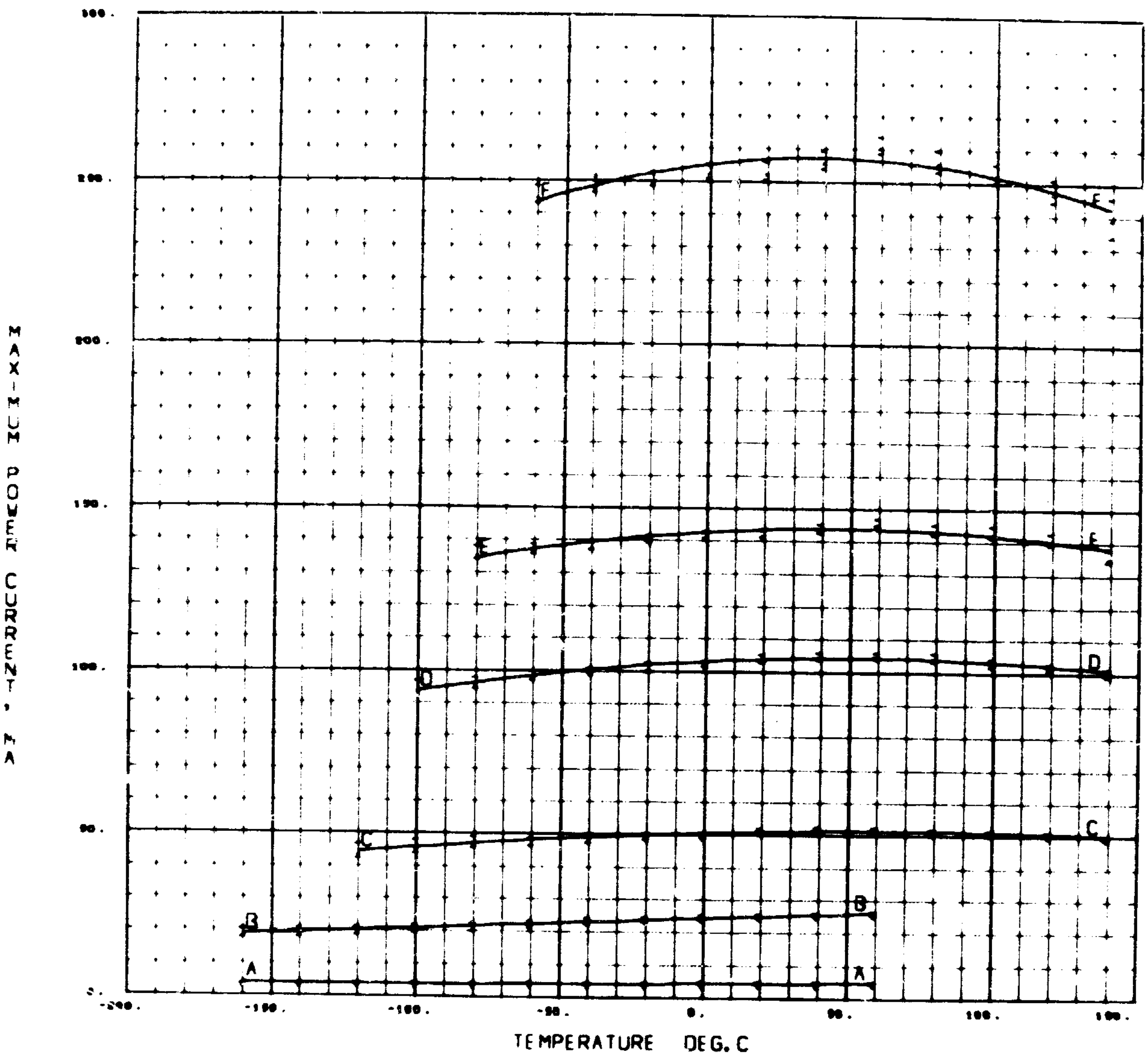
2 OF 3

N77 41 4 UNCLAS



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

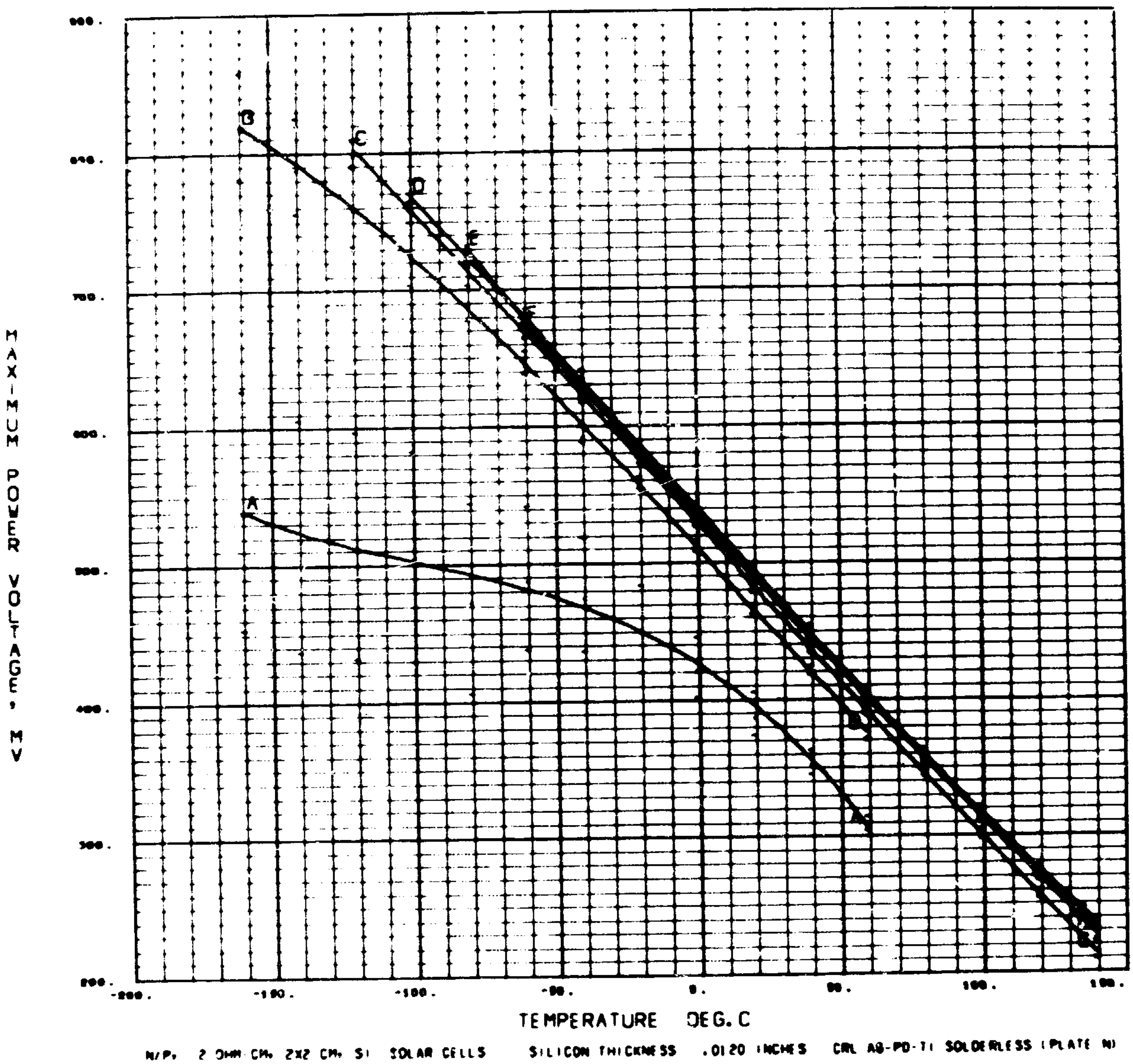
Plate N



N/P, 2 OHM CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES CRL AG-PD-TI SOLDERLESS (PLATE N)

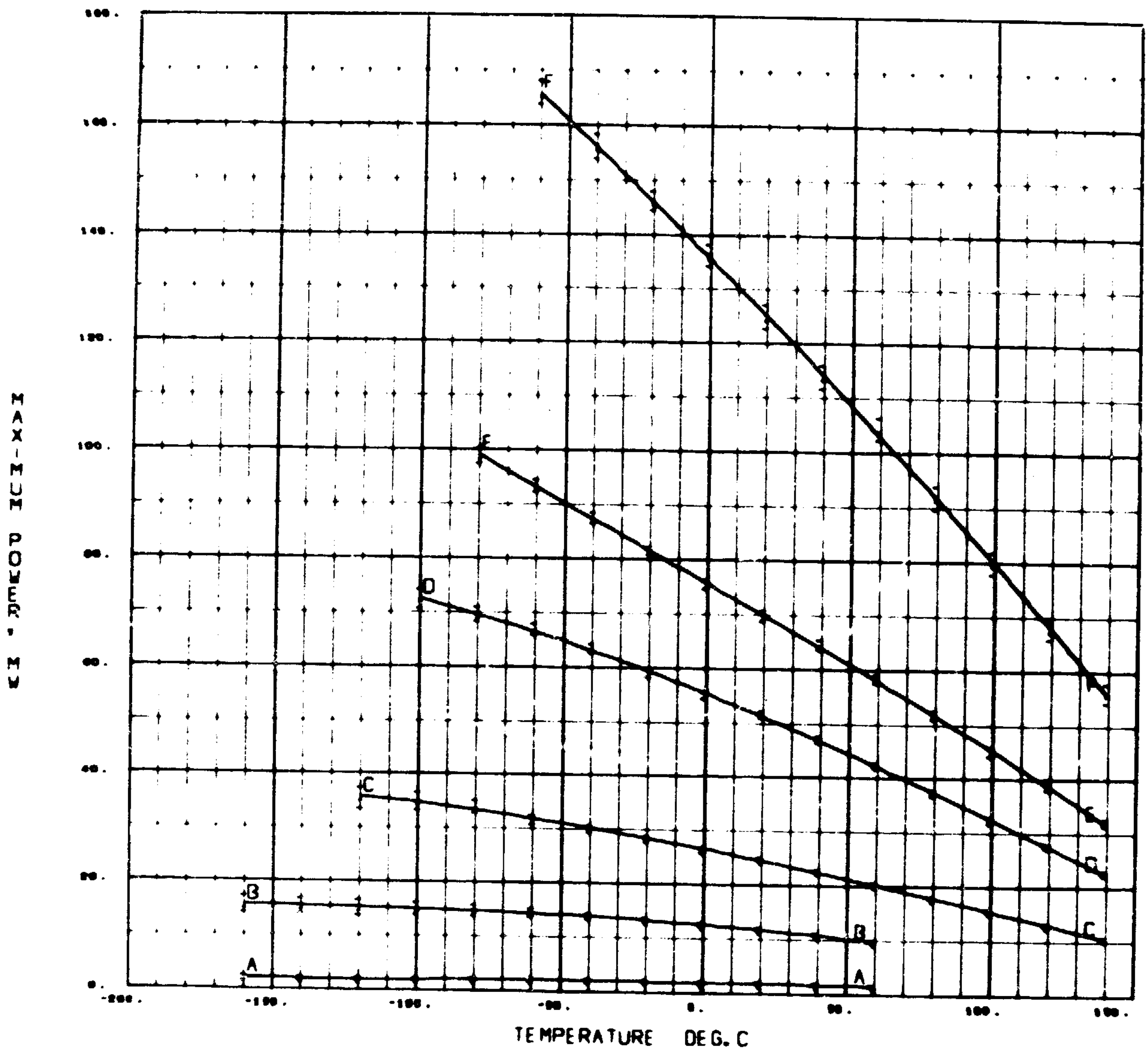
CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate N



CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

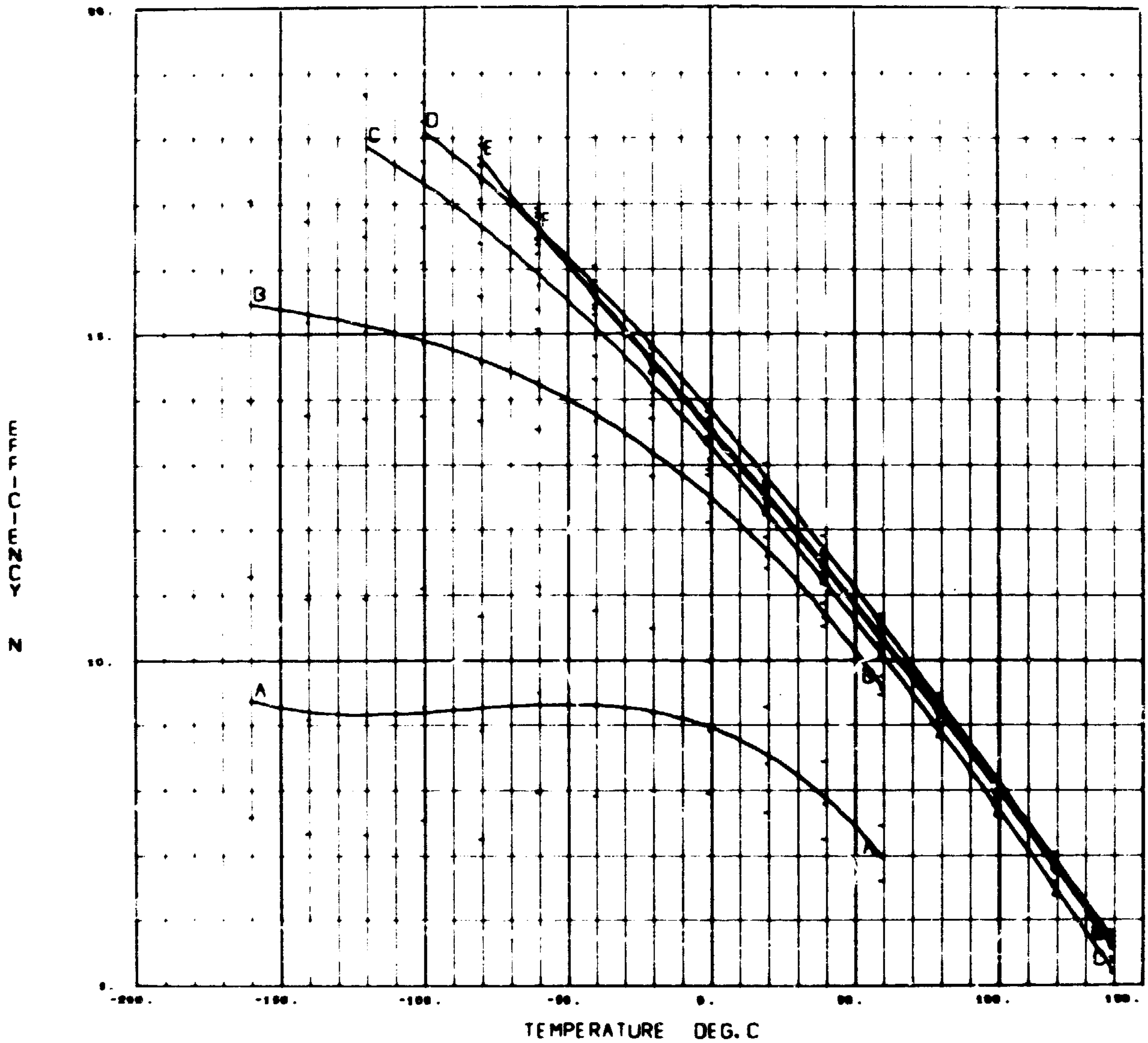
Plate N



N/P, 2 OHM CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES CRL AG-PD-TI SOLDERLESS (PLATE N)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

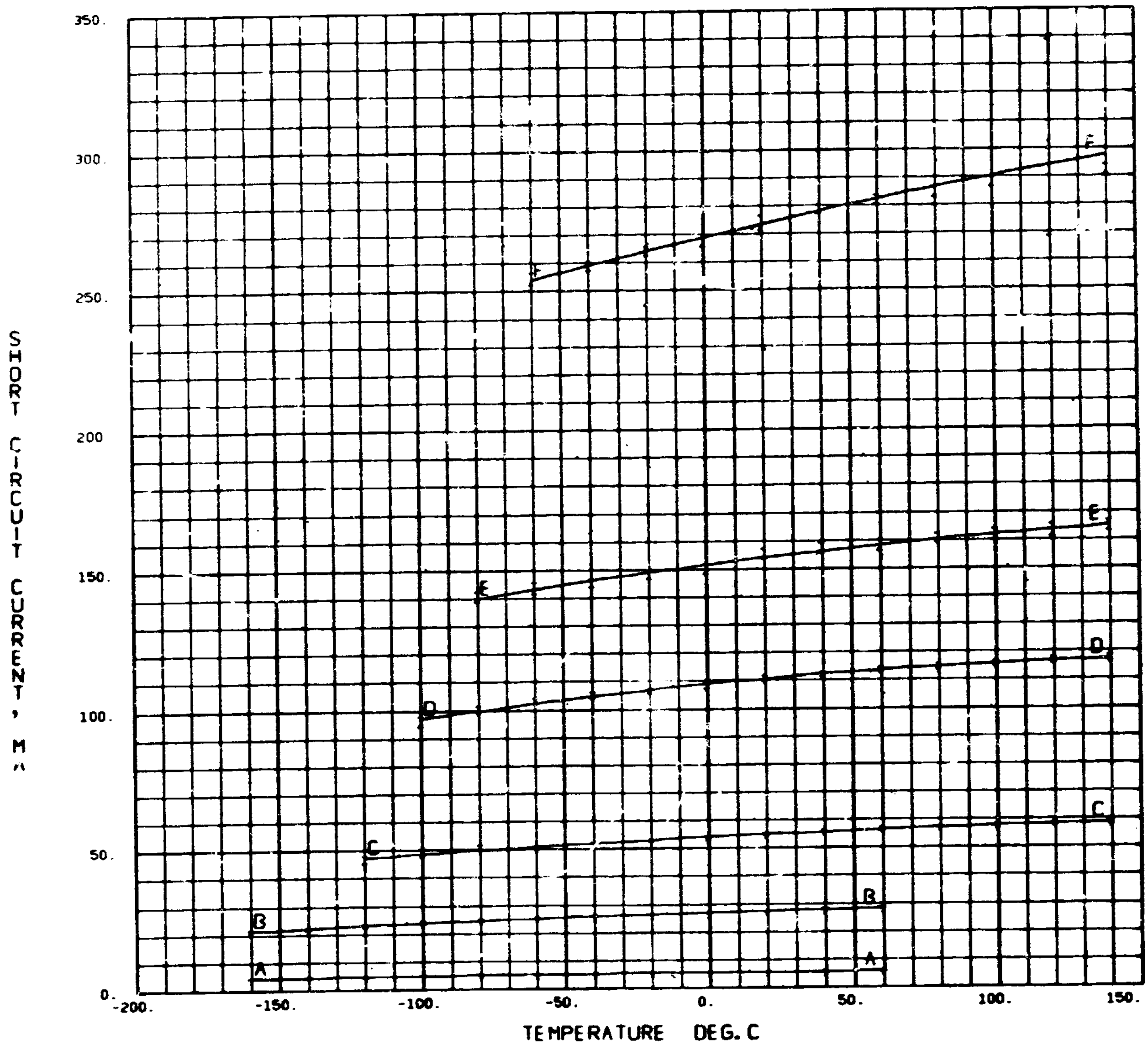
Plate N



N/P, 2 OHM CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES CRL AG-PD-TI SOLDERLESS (PLATE N)

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

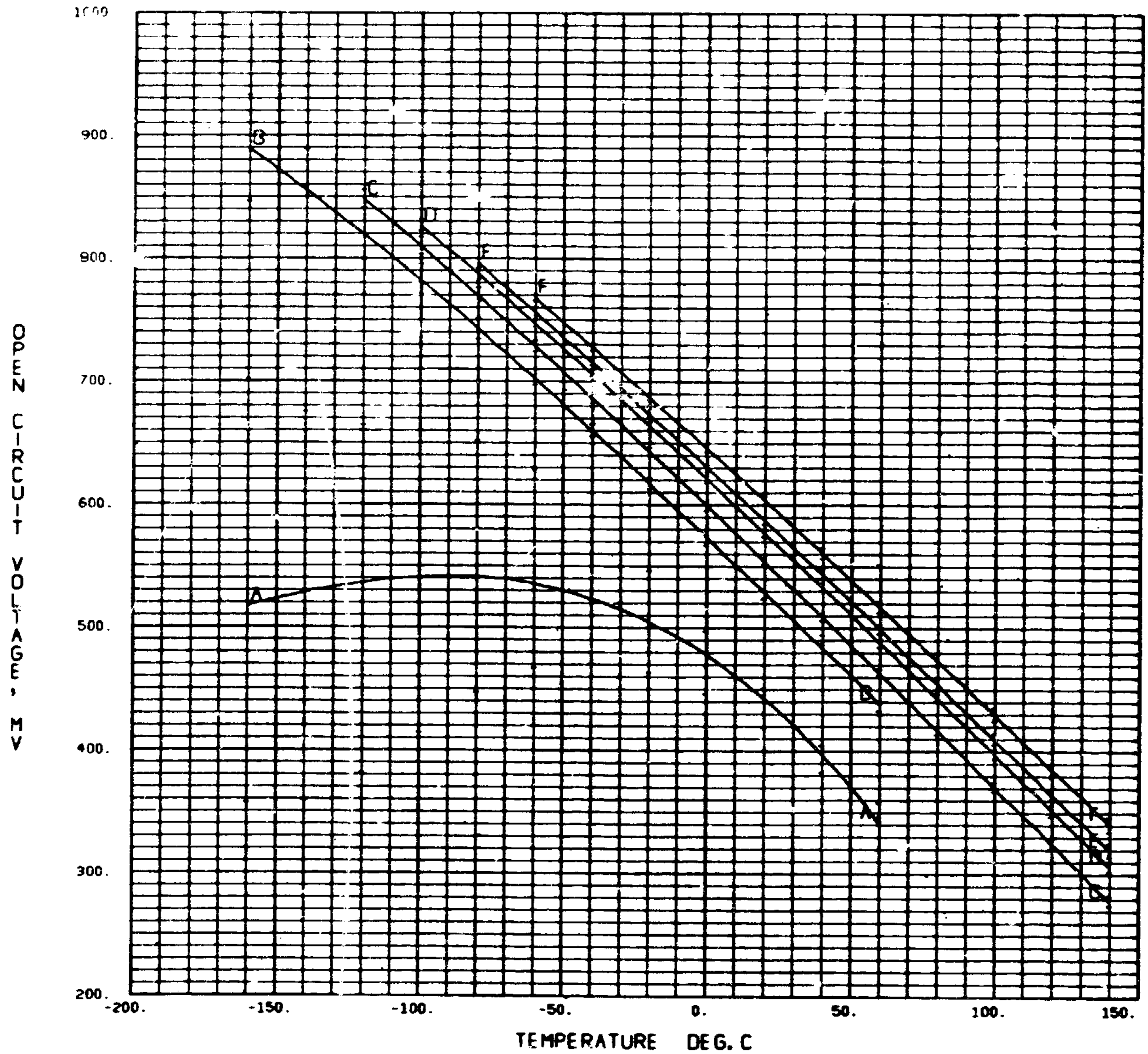
Plate O



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES HEK AG-PD-TI N/S HELIOS FILT.IP-01

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

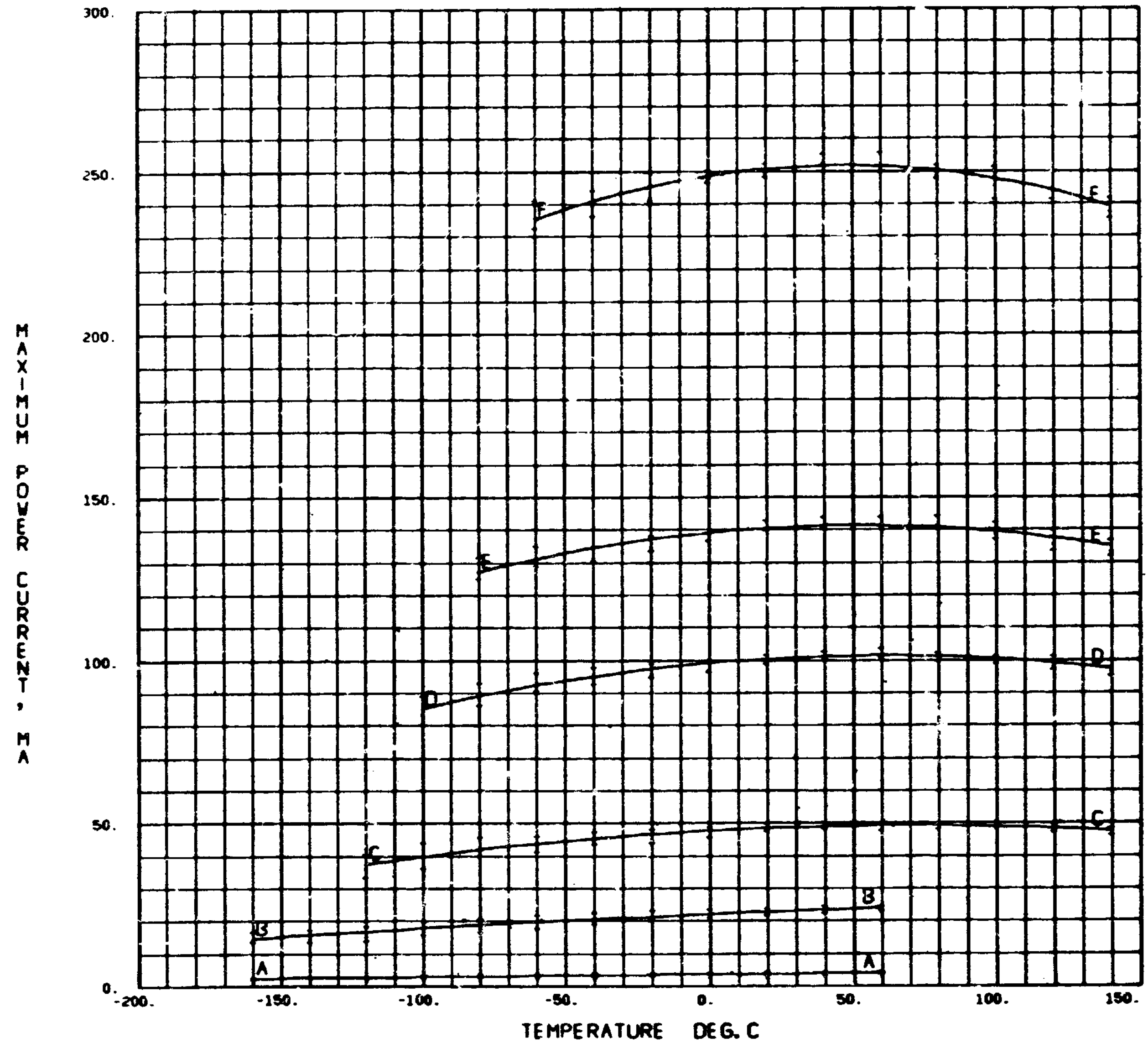
Plate O



N/P, 10 OHM-CM, 2X2 CM SI SOLAR CELLS SILICON THICKNESS .0120 INCHES HEK AG-PD-TI N/S HELIOS FILT.IP-01

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

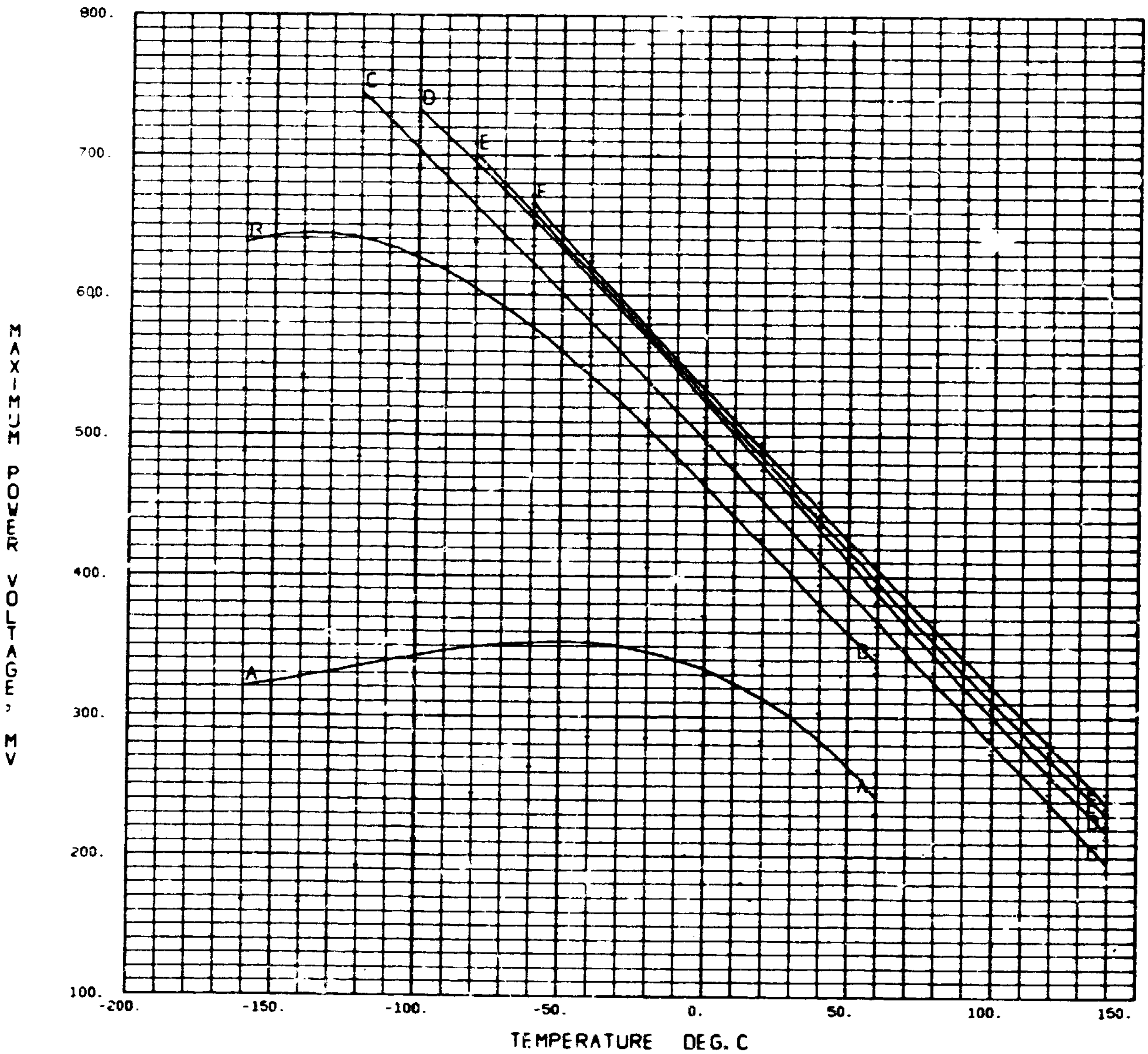
Plate O



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES HEK AG-PD-TI W/S HELIOS FILT.IP-00

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

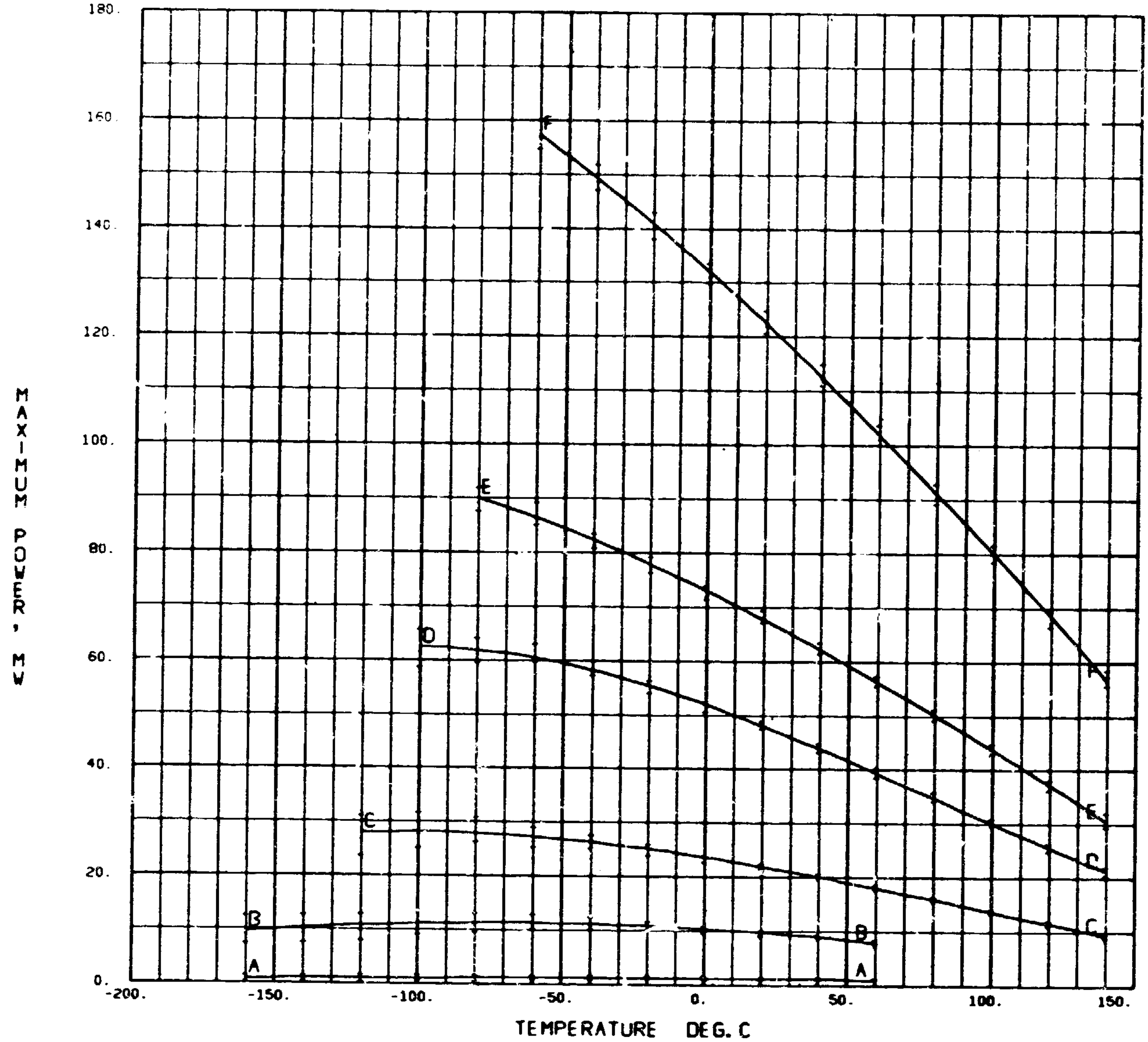
Plate O



N/P 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES HEK AG-PD-TI N/S HELIOS FILT, IP-OI

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

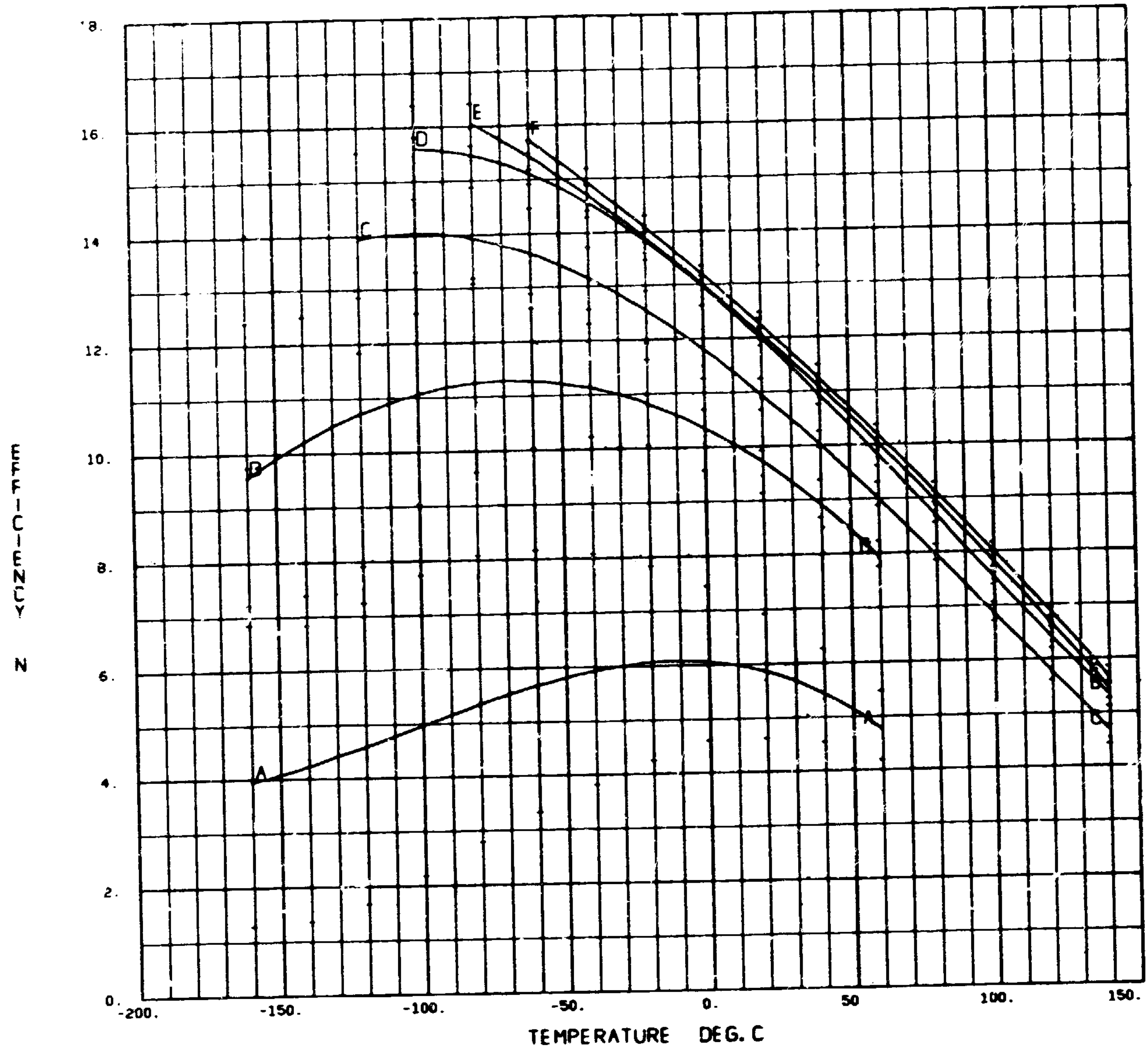
Plate O



N/P, 10 OHM-CM, 2X2 CM, SI SOLAR CELLS SILICON THICKNESS .0120 INCHES HEK AG-PD-TI W/S HELIOS FILT, IP-01

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

Plate O



N/P, 10 OHM-CM, 2X2 CM. SI SOLAR CELLS SILICON THICKNESS .0120 INCHES HEK AG-PD-TI N/S HELIOS FILT.IP-0I

CURVE ID	A	B	C	D	E	F
ILLUMINATION INTENSITY (SOLAR CONSTANT)	0.0357	0.1786	0.3571	0.7143	1.000	1.7857

3.3 IRRADIATED SILICON SOLAR CELLS

3.3.1 I_{sc}, I_{mp}, V_{mp}, V_{oc}, and P_{mp} of Conventional, Field, and Hybrid Cells versus 1-MeV Fluence (Ref. 3.3-1)

Cell Description

Solar Cells: Per Table 3.3-1

Cell Material: Crucible-grown silicon

Cell Manufacturer: Heliotek/Spectrolab

Cover: As marked without cover or with cover

Cover Type for Hybrid and Field Cells: 0.30 mm thick fused silica (Corning 7940) with 0.35 μm cut-on blue filter and MgF_2 antireflecting coating

Cover Type for Conventional Cells: Same as above except 0.41 μm cut-on blue filter

Cover Adhesive: DC 93-500 for hybrid and field cells; R6-3489 for conventional cells

Sample Size: Five cells of each type

Test Equipment

Spectrolab Mark 3 Solar Simulator

Hughes Pulse Xenon Solar Simulator (Ref. 3.3-2)

Dynamition Particle Accelerator (JPL)

Test Results

The test results are given in the figures listed below.

3.3-1 Output Parameters of Hybrid Cells versus 1-MeV Fluence (Solid lines represent data for unglassed cells; circles represent data for glassed cells)

3.3-2 Output Parameters of Field Cells versus 1-MeV Fluence (Solid lines represent data for unglassed cells; circles represent data for glassed cells)

3.3-3 Comparative Output of Three Solar Cell Types (data is shown for 20 x 20 mm equivalent cell size, annealed and unglassed condition. For glassing losses or gains, see Section 4.3.3 in Volume I)

Table 3.3-1. Solar Cell Specimen Description (Ref. 3.3-1)

Cell Type	Hybrid	Field	Conventional
Specimen Code	A	B	C
Cell Size (mm)	22 x 20	22 x 20	20 x 20
Cell Thickness (mm)	0.30	0.30	0.30
Base Resistivity (ohm·cm)	7.8 - 13.0	11.6 - 25.0	7.8 - 13.0
p^+ Field	No	Yes	No
Junction Depth (μm)	0.15	0.2	0.3
Contact Material	Ti-Pd-Ag	Ti-Pd-Ag	Ti-Ag
Cell Coating	Ta_2O_5	Ta_2O_5	SiO_x

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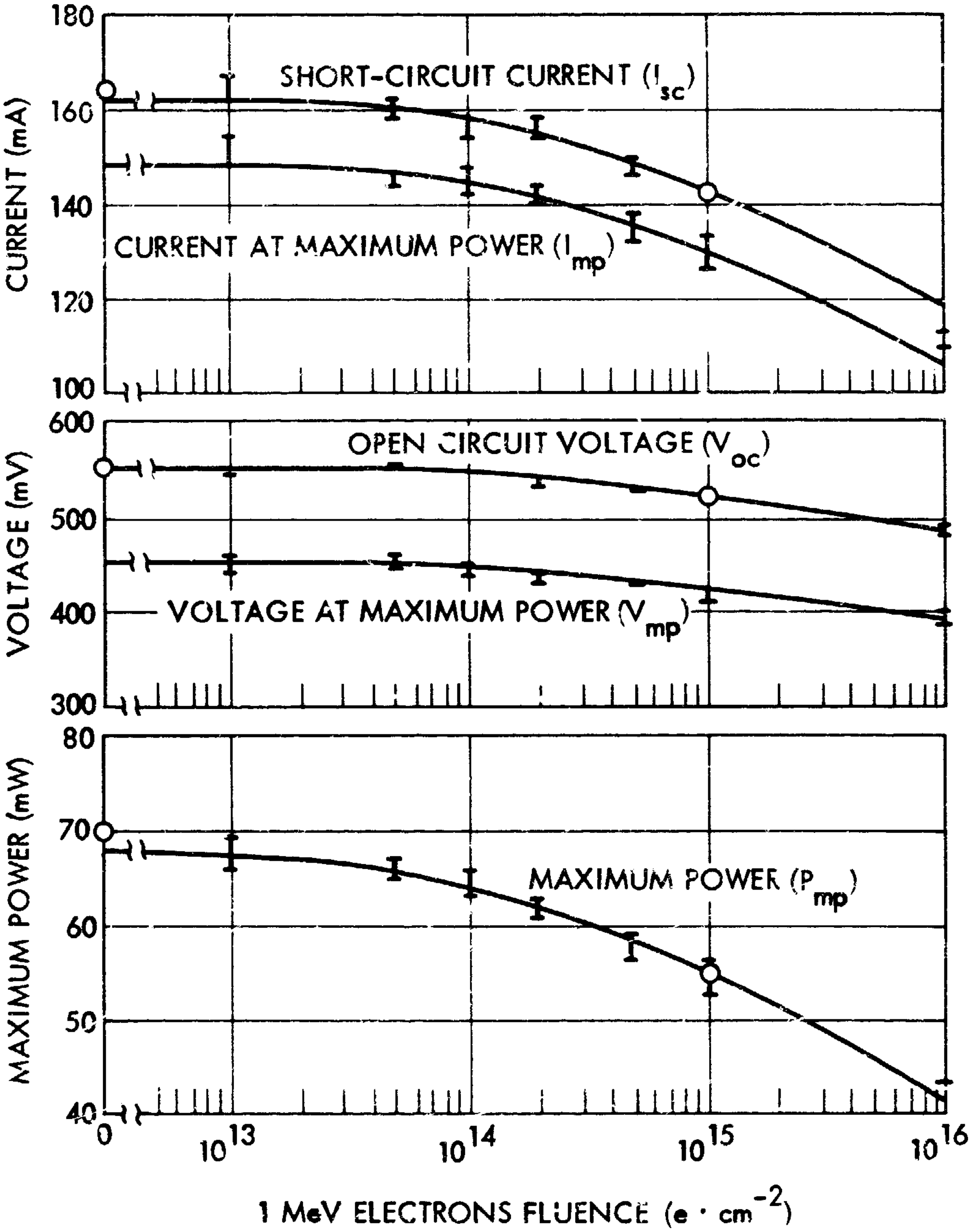

Figure 3.3-1. Output Parameters of Hybrid Cells Versus 1-MeV Fluence (Solid lines represent data for unglassed cells; circles represent data for glassed cells)

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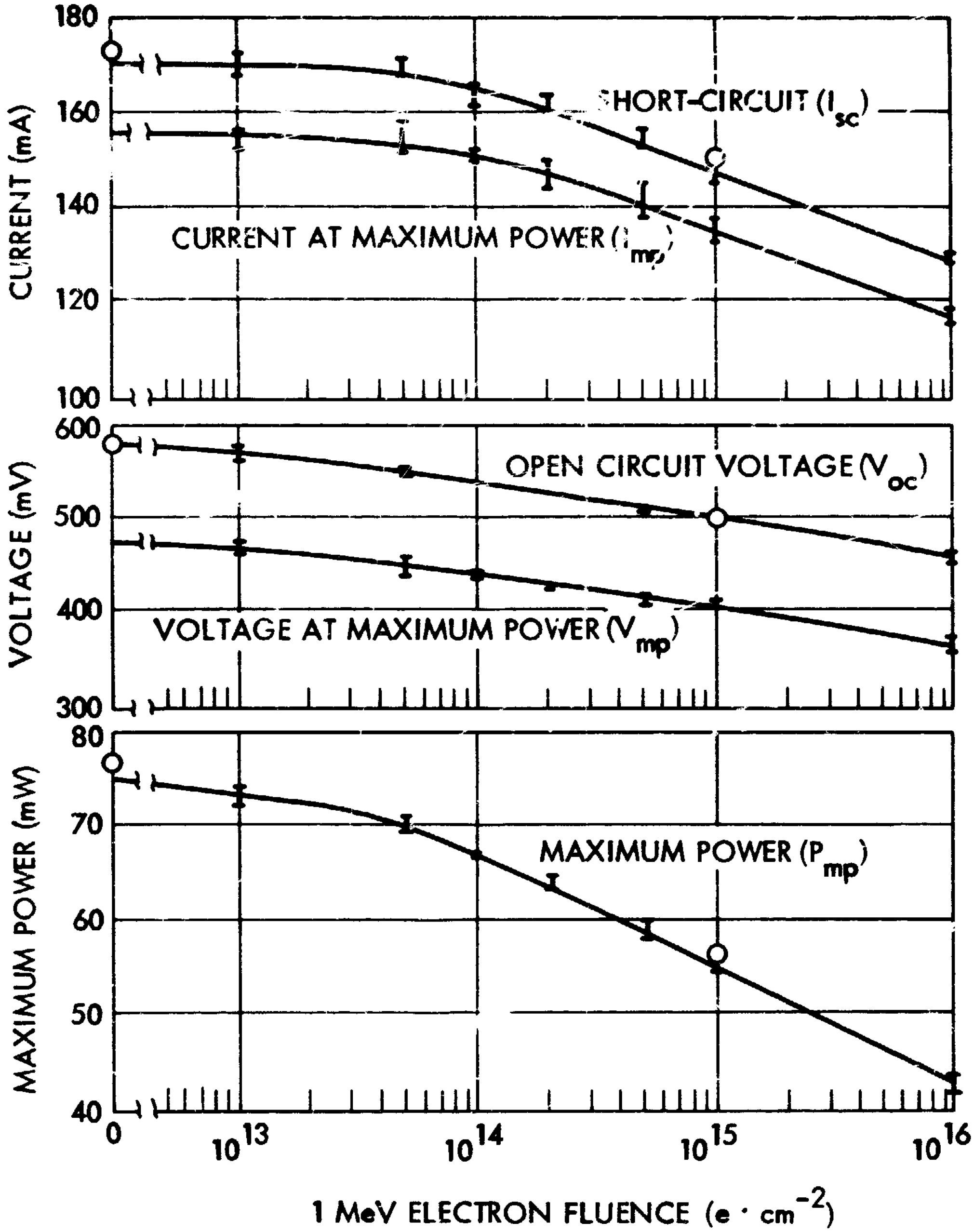

Figure 3.3-2. Output Parameters of Field Cells Versus 1-MeV Fluence (Solid lines represent data for unglassed cells; circles represent data for glassed cells)

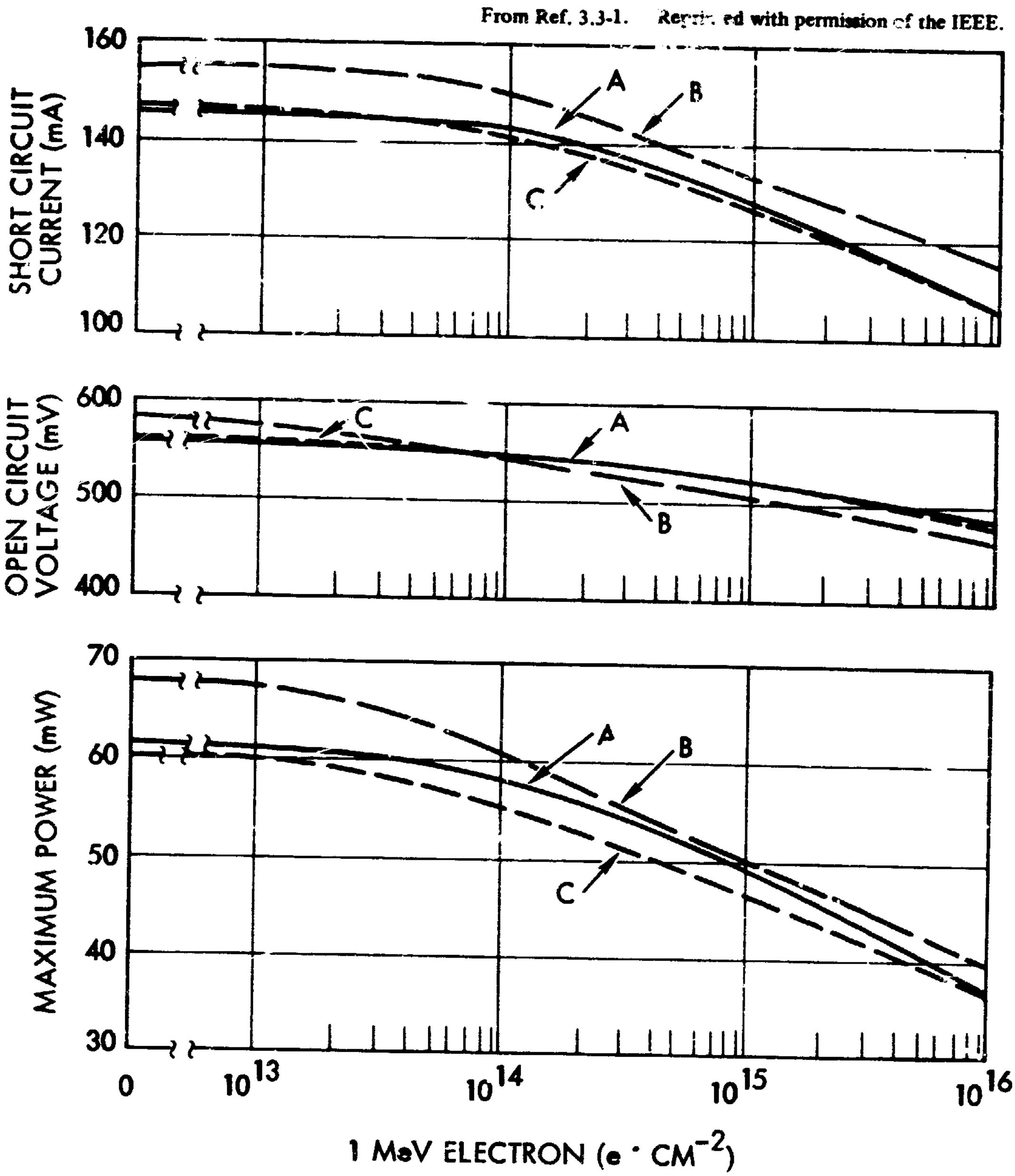

Figure 3.3-3. Comparative Output of Three Solar Cell Types (data is shown for 20 x 20 mm equivalent cell size, annealed and unglassed condition. For glassing losses or gains, see Section 4.3.3 in Volume I)

3.4 THIN SILICON CELLS

3.4.1 Performance of Conventional Unirradiated 2 and 10 ohm·cm N-on-P Cells with SiO Coating (Ref. 3.4-1)

Cell Description

Polarity: n-on-p

Cell Fabrication Process: Same as used for similar cells having greater thickness

Cell Size: 2 x 2 cm

Active Area: 3.9 cm^2

Cell Thickness: 0.10 to 0.30 mm (0.004 to 0.012 inch)

Base Resistivity: 2 (1 to 3) ohm·cm and 10 (7 to 14) ohm·cm boron-doped, crucible-grown

Contacts: Ti-Ag, solderless, gridded

Antireflective Coating: SiO

Coverglass: None

Test Setup

Illumination: X-25L Spectrosun AM0 Solar Simulator

Intensity Calibration: Using balloon-calibrated standard cell

Cell Holder: Four-terminal clamp with heat sink, mounted in dry nitrogen-flushed, thermally insulated box covered with quartz window

Temperature Calibration: Using thermocouples on cell and on cell heat sink block

Experimental Results

The experimental results are shown in the following figures:

3.4-1 Typical I-V Curves at 1 Solar Constant Intensity and at 28°C Cell Temperature

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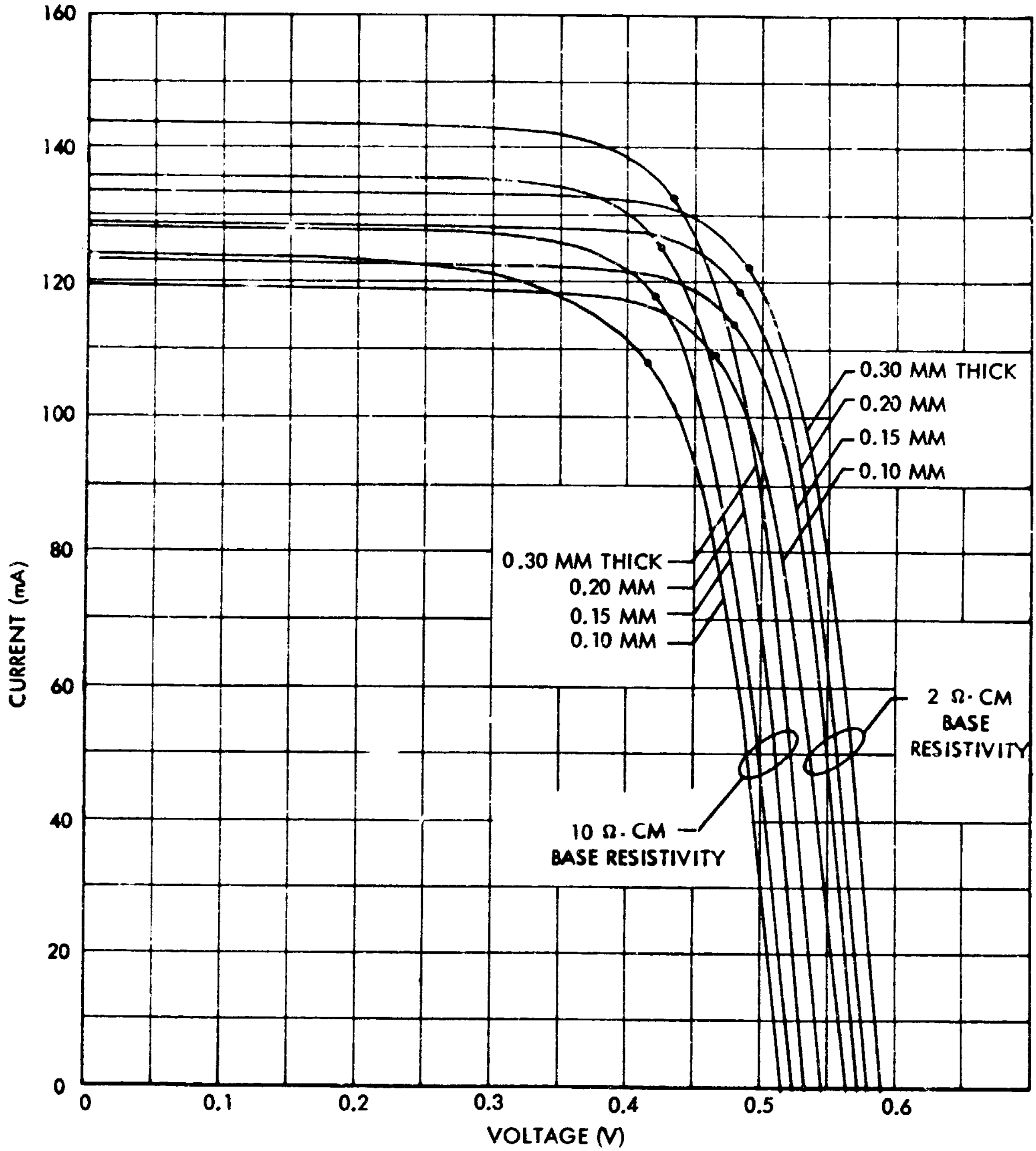

Figure 3.4-1. Typical I-V Curves at 1.00 Solar Constant Intensity and at 28°C Cell Temperature

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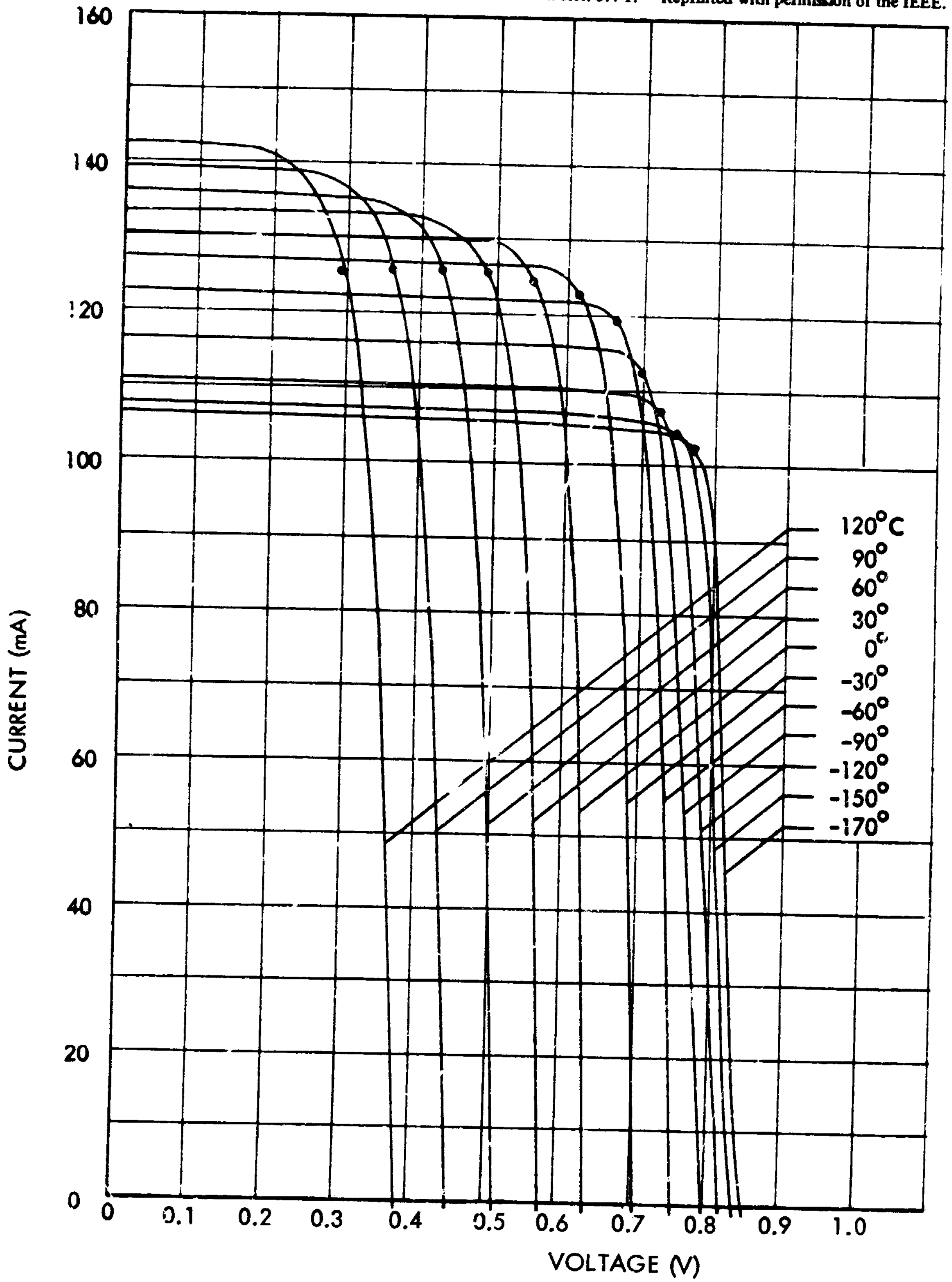

Figure 3.4-2. Typical I-V Curves of 0.30 mm Thick, 2 ohm·cm Cells versus Temperature at 1.00 Solar Constant Intensity

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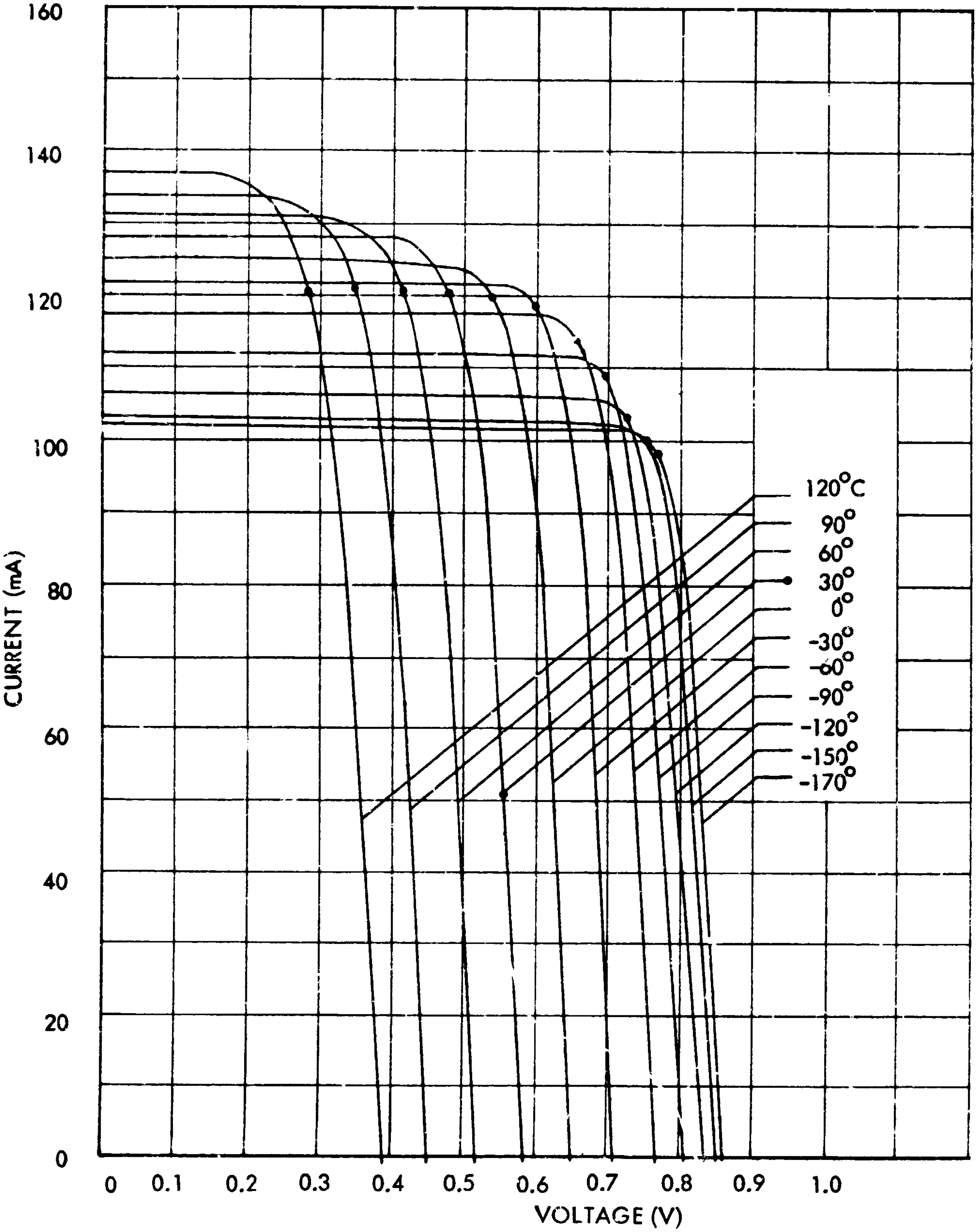

Figure 3.4-3. Typical I-V Curves of 0.20 mm Thick, 2 ohm·cm Cells versus Temperature at 1.00 Solar Constant Intensity

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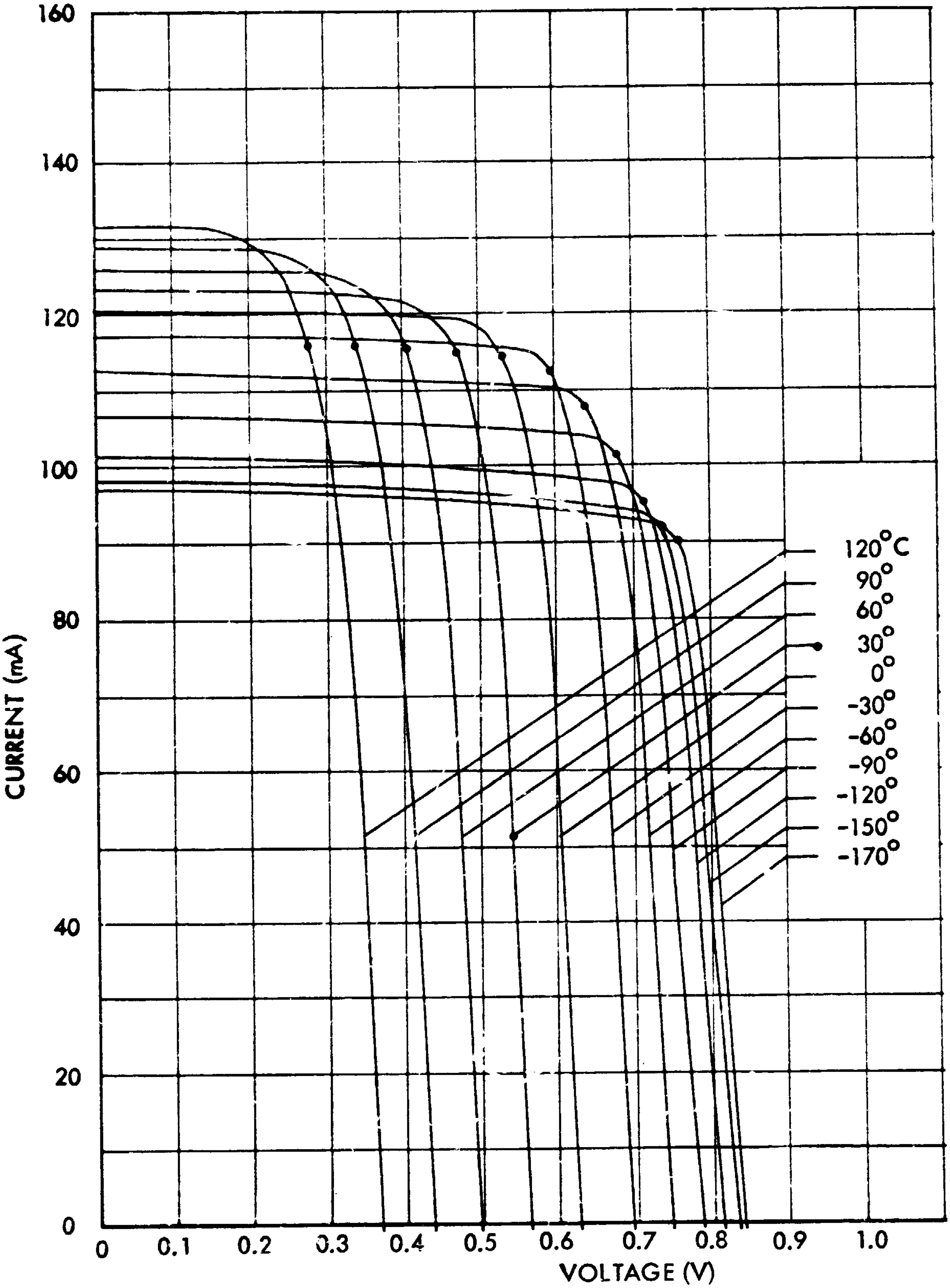

Figure 3.4-4. Typical I-V Curves of 0.15 mm Thick, 2 ohm·cm Cells versus Temperature at 1.00 Solar Constant Intensity

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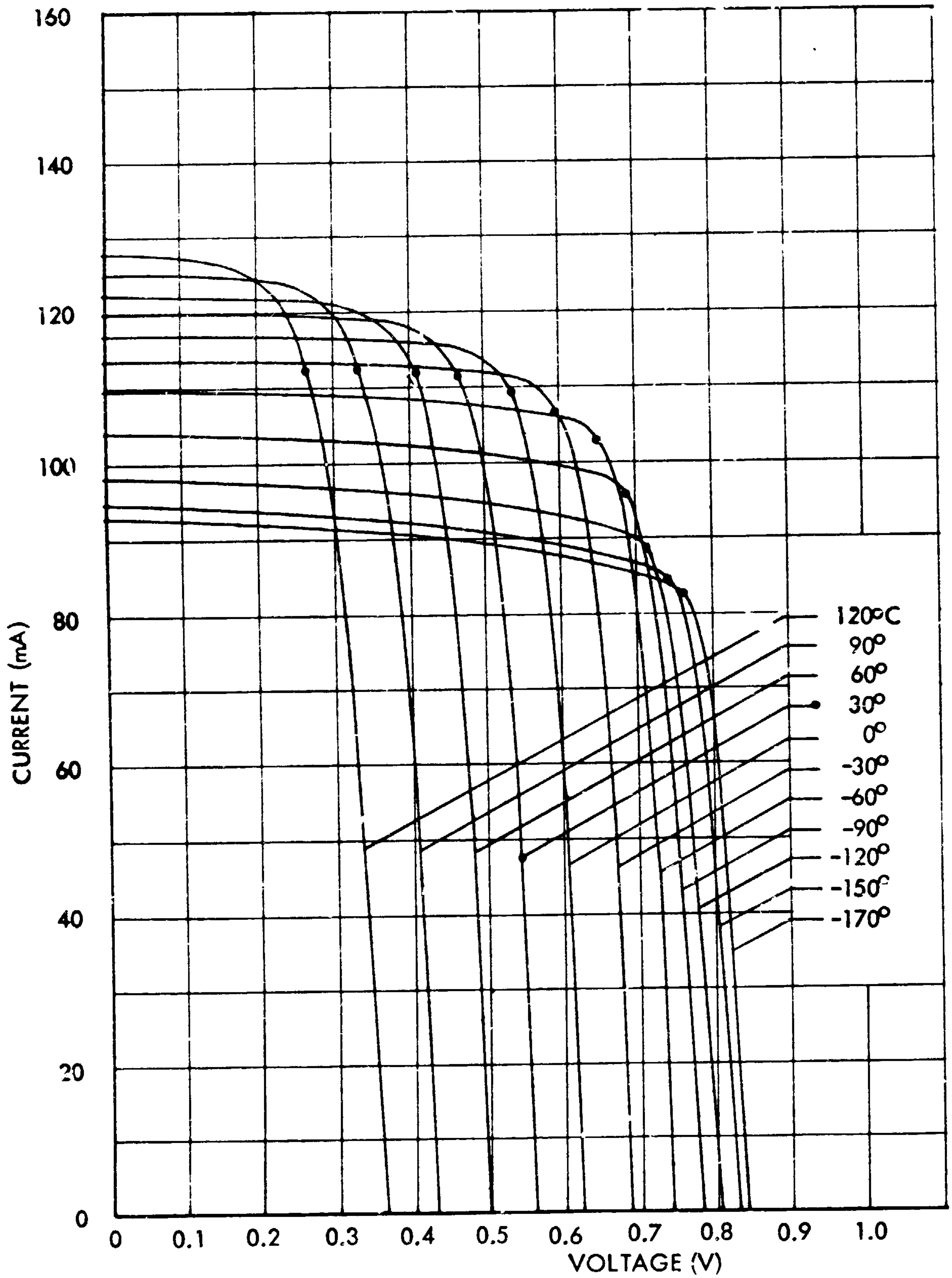

Figure 3.4-5. Typical I-V Curves of 0.10 mm Thick, 2 ohm · cm Cells versus Temperature at 1.00 Solar Constant Intensity

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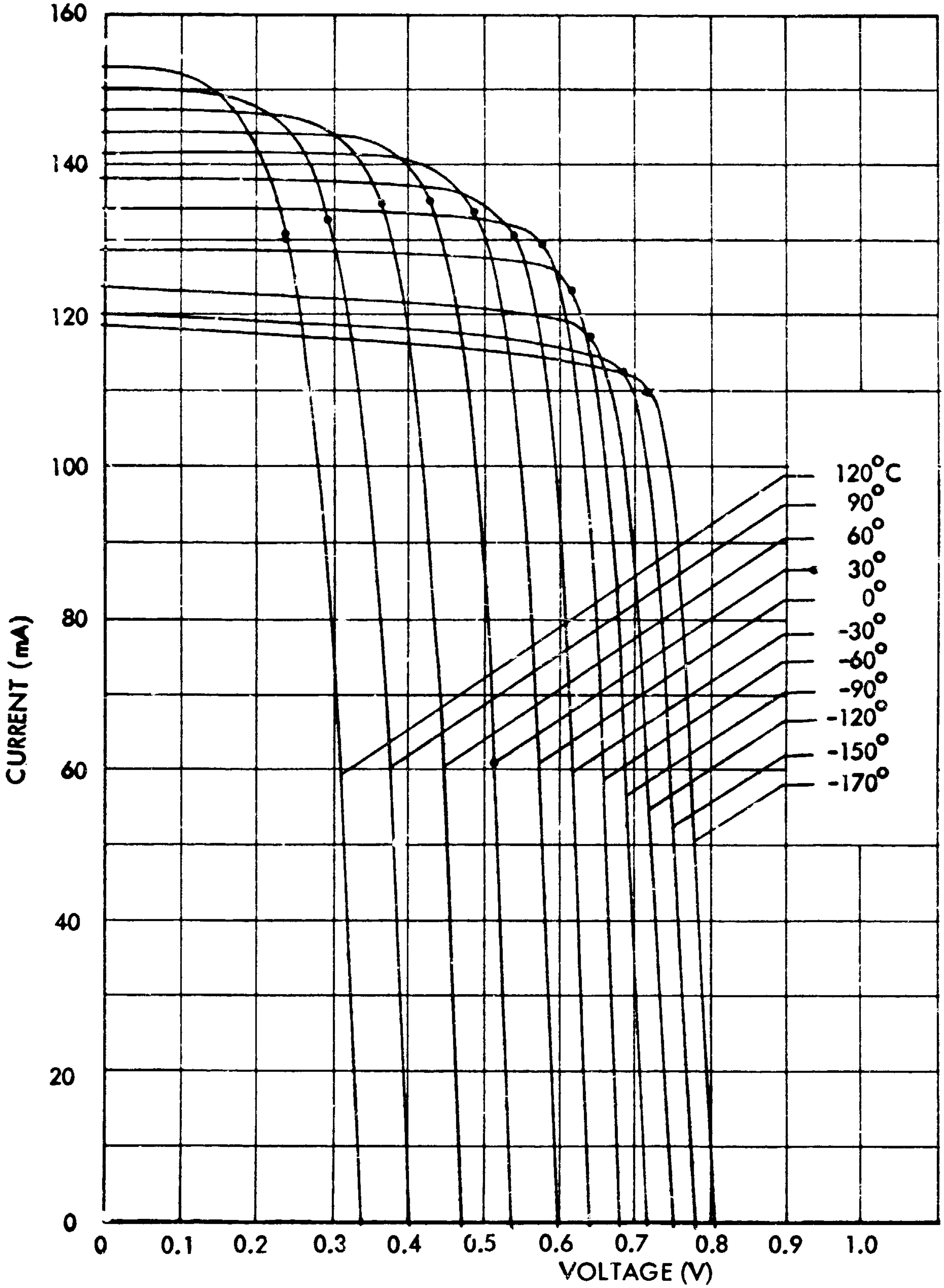

Figure 3.4-6. Typical I-V Curves of 0.30 mm Thick, 10 ohm · cm Cells versus Temperature at 1.00 Solar Constant Intensity

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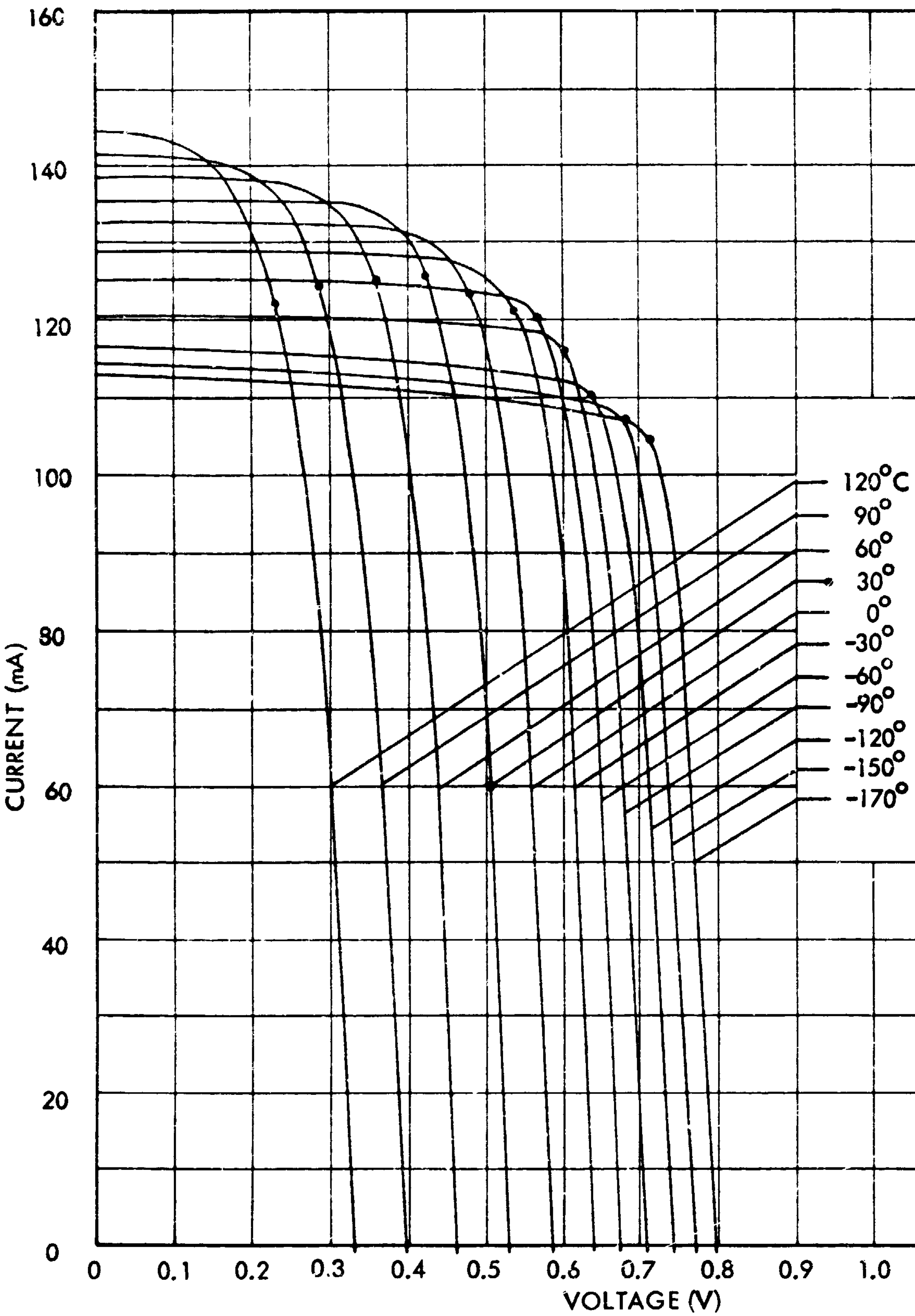

Figure 3.4-7. Typical I-V Curves of 0.20 mm Thick, 10 ohm · cm Cells versus Temperature at 1.00 Solar Constant Intensity

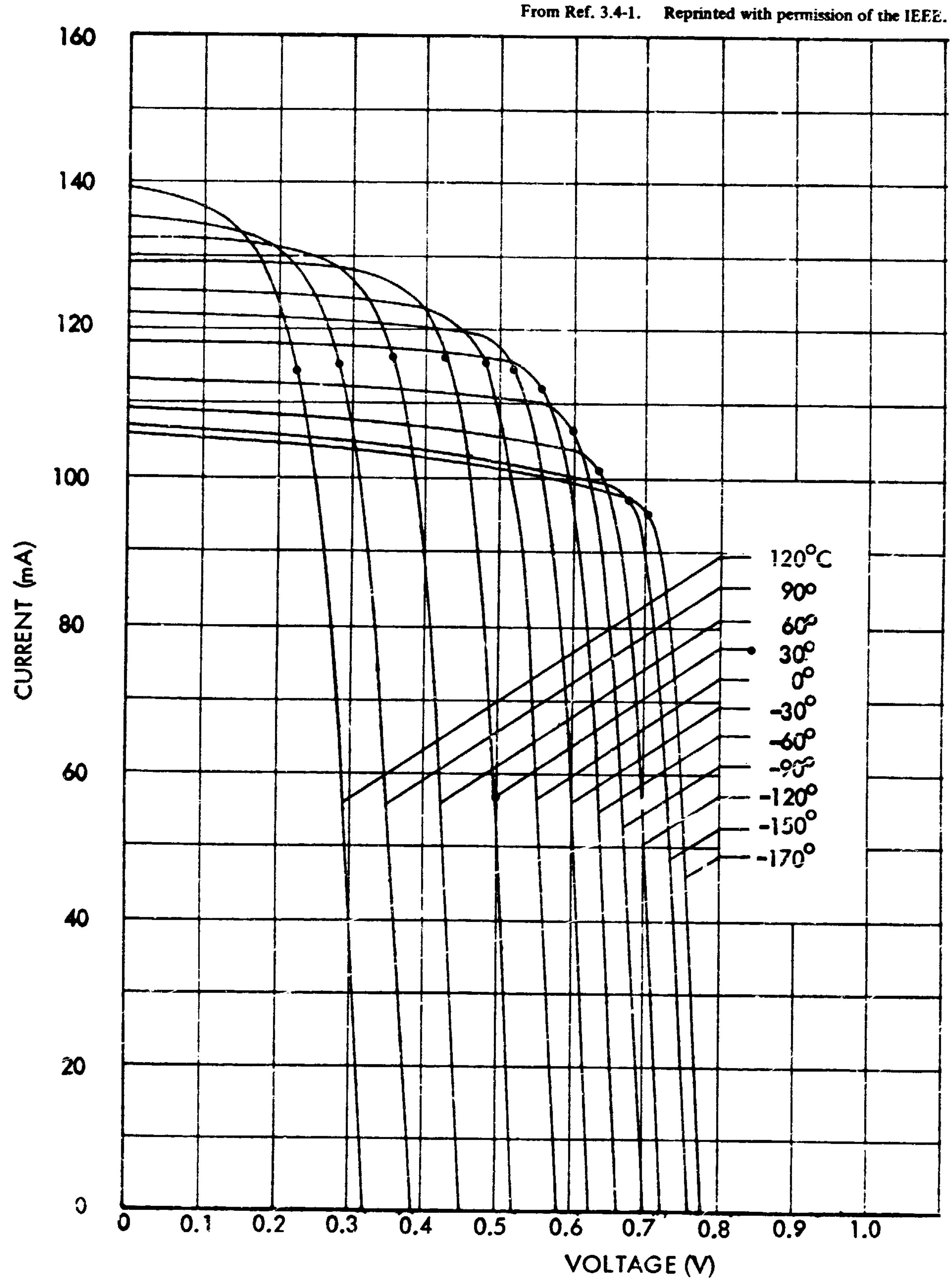

Figure 3.4-8. Typical I-V Curves of 0.45 mm Thick, 10 ohm · cm Cells versus Temperature at 1.00 Solar Constant Intensity

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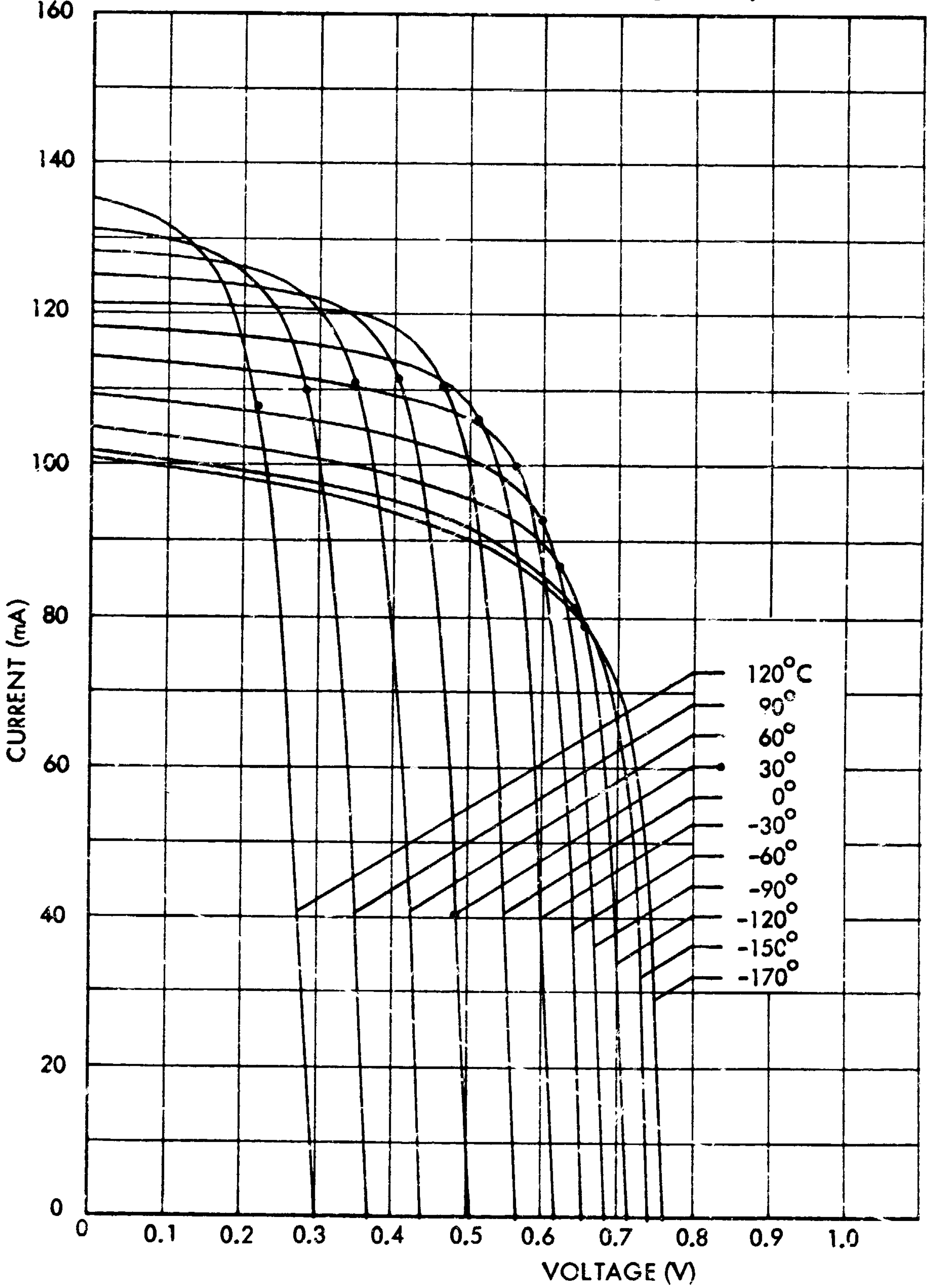

Figure 3.4-9. Typical I-V Curves of 0.10 mm Thick, 10 ohm · cm Cells versus Temperature at 1.00 Solar Constant Intensity

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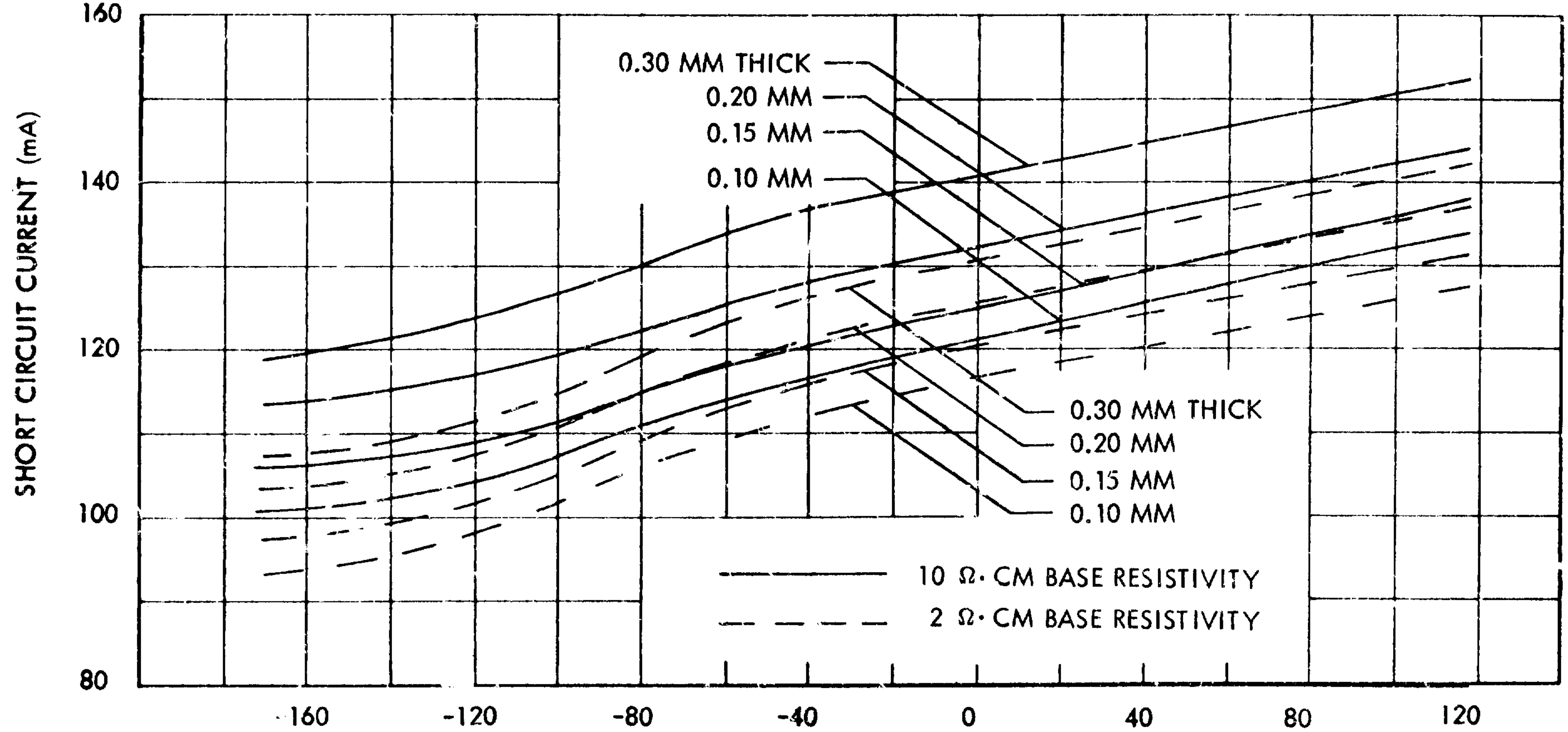

Figure 3.4-10. Short-circuit Current versus Temperature at 1.00 Solar Constant Intensity

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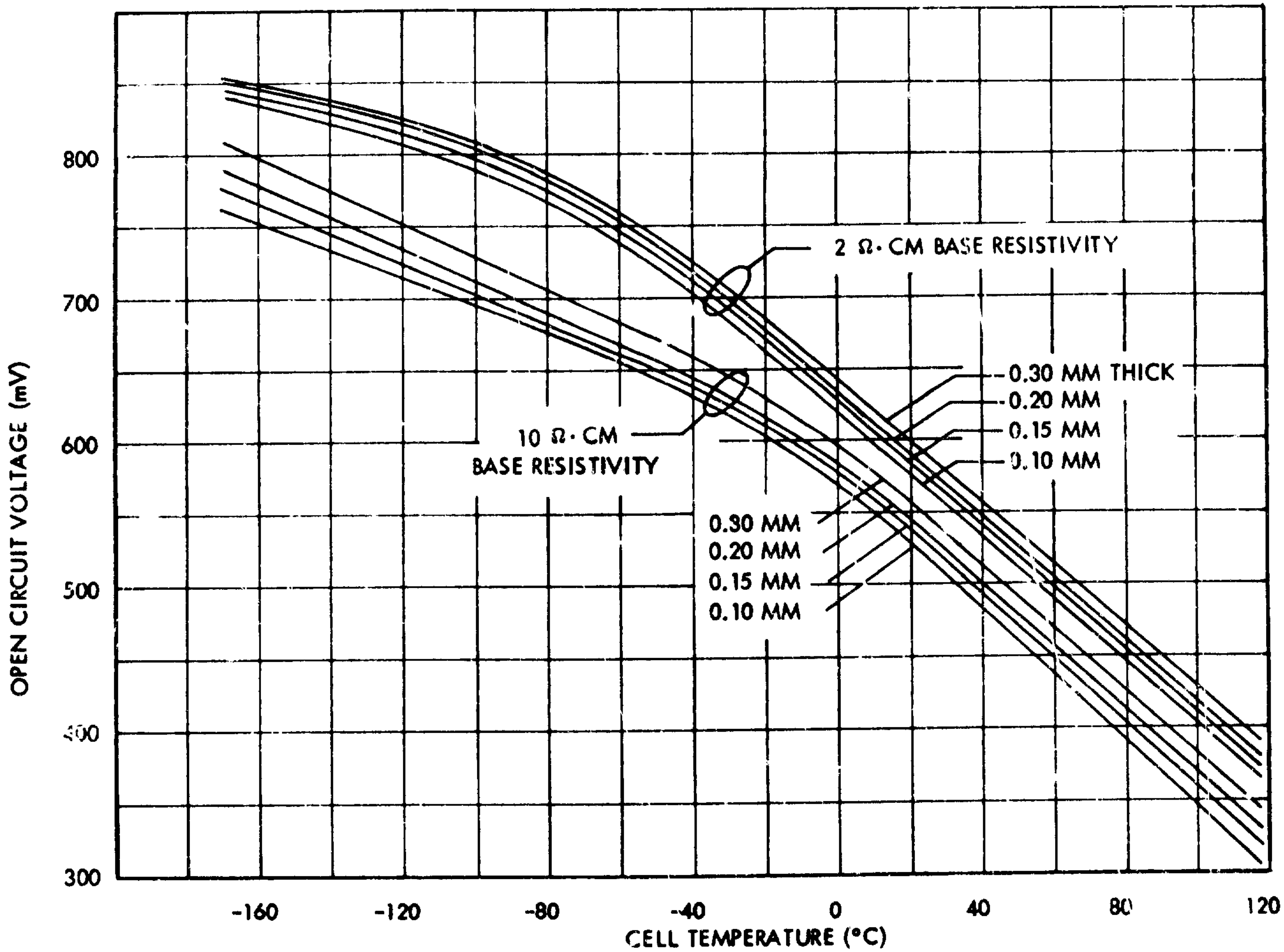

Figure 3.4-11. Open-circuit Voltage versus Temperature at 1.00 Solar Constant Intensity

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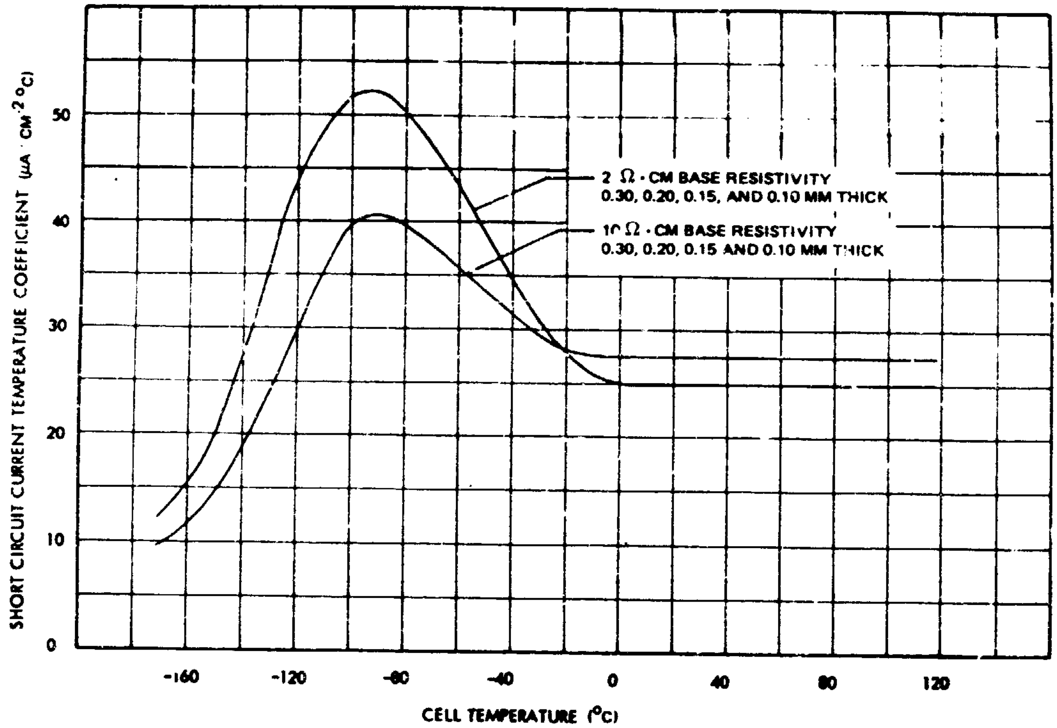

Figure 3.4-12. Short-circuit Current Temperature Coefficients versus Temperature at 1.00 Solar Constant Intensity

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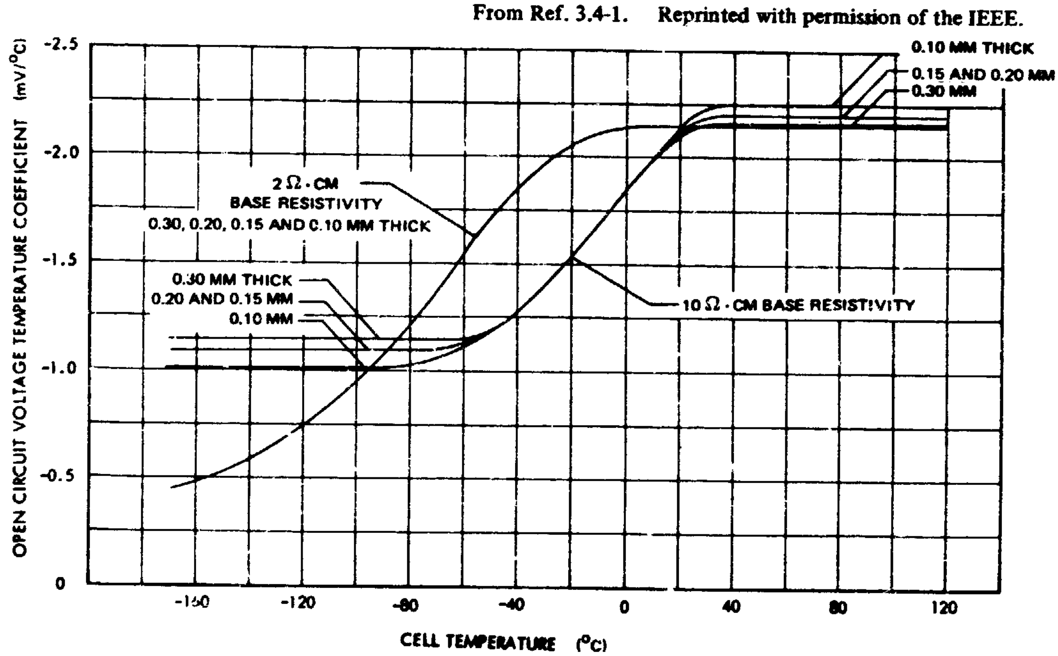

Figure 3.4-13. Open-circuit Voltage Temperature Coefficients versus Temperature at 1.00 Solar Constant Intensity

3.4.2 Applied Physics Laboratory Data for Irradiated 2 and 10 ohm·cm N-on-P Cells with SiO Coating (Ref. 3.4-2)

Cell Description

Seven cells in each resistivity and thickness group from the cells described in Section 3.4.1 were tested; five of each of them were irradiated. Actual cell thickness per Table 3.4-1.

Test Setup

Illumination: OCLI AM0 Solar Simulator

Radiation Type: 1-MeV electrons

Radiation Source: Van de Graaff generator, Naval Research Laboratory

Spectral Response Apparatus: Heliotek Filter Wheel Monochromator

Experimental Results

The experimental results are shown in the following tables and figures:

Table 3.4-2	Performance of 10 ohm·cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature
Table 3.4-3	Performance of 2 ohm·cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature
Table 3.4-4	Average Temperature Coefficients of 2 and 10 ohm·cm Cells at 1 Solar Constant Intensity (Applicable for the Range from 13° to 54°C only)
Figure 3.4-14	Maximum Power Output versus Fluence for 2 and 10 ohm·cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature
Figure 3.4-15	Power Output at 0.4 Volts versus Fluence for 2 and 10 ohm·cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature
Figure 3.4-16	Power Output at 0.35 Volts versus Fluence for 2 and 10 ohm·cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature
Figure 3.4-17	Spectral Response at 10 ohm·cm Cells Before and After Irradiation to 5.1×10^{15} 1-MeV Electrons per cm^2, at 25°C
Figure 3.4-18	Spectral Response of 2 ohm·cm Cells Before and After Irradiation to 5.1×10^{15} 1-MeV Electrons per cm^2, at 25°C

Table 3.4-1. Ranges of Silicon Wafer Thicknesses and Metric Conversion for Solar Cells in Tables 3.4-2 Through 3.4-4 and in Figures 3.4-14 Through 3.4-18.

2 ohm·cm Base Resistivity			
Average		Minimum	Maximum
(Inch)	(mm)	(mm)	(mm)
0.0118	0.2997	0.2946	0.3048
0.0071	0.1803	0.1727	0.1880
0.0057	0.1484	0.1321	0.1575
0.0034	0.0864	0.0737	0.0914

10 ohm·cm Base Resistivity			
Average		Minimum	Maximum
(Inch)	(mm)	(mm)	(mm)
0.0120	0.3048	0.2997	0.3099
0.0078	0.1981	0.1905	0.2083
0.0060	0.1524	0.1422	0.1626
0.0037	0.0939	0.0838	0.0991

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Table 3.4-2. Performance of 10 ohm·cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature

	I_{sc} (mA)				V_{oc} (V)				P_{max} (mW)				Volts at P_{max}			
Wafer Thickness (Inches)	0.012	0.0078	0.006	0.0037	0.012	0.0078	0.006	0.0037	0.012	0.0078	0.006	0.0037	0.012	0.0078	0.006	0.0037
$\phi = 0$	136.9	131.1	125.7	120.2	0.534	0.524	0.510	0.499	53.4	49.6	46.4	42.0	0.425	0.420	0.408	0.404
$\phi = 1.3 \times 10^{13}$	138.1	131.1	126.5	120.9	0.530	0.515	0.504	0.501	53.3	49.5	46.5	42.4	0.424	0.412	0.400	0.405
$\phi = 5.3 \times 10^{13}$	135.9	131.0	125.9	121.0	0.526	0.519	0.507	0.503	51.5	48.8	46.1	42.5	0.420	0.415	0.407	0.405
$\phi = 10^{14}$	134.2	129.1	125.5	121.1	0.524	0.518	0.507	0.503	50.0	48.1	45.8	42.5	0.417	0.410	0.405	0.405
$\phi = 10^{15}$	119.1	117.5	116.6	116.1	0.494	0.495	0.488	0.491	40.9	40.9	40.0	39.4	0.386	0.386	0.387	0.394
$\phi = 5.1 \times 10^{15}$	106.3	104.3	104.2	105.8	0.470	0.470	0.466	0.468	34.7	34.4	34.3	34.0	0.365	0.370	0.367	0.377

ϕ = Integrated number of 1 MeV $e \cdot cm^{-2}$

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Table 3.4-3. Performance of 2 ohm·cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature

Wafer Thickness (Inches)	I_{sc} (mA)				V_{oc} (V)				P_{max} (mW)				Volts at P_{max}			
	0.0118	0.0071	0.0057	0.0034	0.0118	0.0071	0.0057	0.0034	0.0118	0.0071	0.0057	0.0034	0.0118	0.0071	0.0057	0.0034
$\phi = 0$	129.0	121.8	117.9	113.4	0.573	0.570	0.563	0.549	56.8	54.0	52.0	47.2	0.475	0.474	0.474	0.458
$\phi = 1.3 \times 10^{13}$	128.8	121.8	118.5	113.6	0.569	0.566	0.560	0.548	56.5	53.7	52.1	47.1	0.467	0.472	0.466	0.450
$\phi = 5.3 \times 10^{13}$	126.2	120.4	118.4	113.6	0.561	0.563	0.559	0.548	54.3	52.5	51.5	47.1	0.467	0.473	0.472	0.454
$\phi = 10^{14}$	123.6	118.8	116.5	113.2	0.556	0.560	0.557	0.548	52.6	51.3	50.7	46.5	0.461	0.472	0.469	0.452
$\phi = 10^{15}$	108.4	104.6	105.4	105.6	0.523	0.530	0.530	0.529	43.1	42.6	43.3	41.8	0.435	0.449	0.450	0.438
$\phi = 5.1 \times 10^{15}$	92.2	89.9	89.8	91.6	0.495	0.507	0.507	0.506	34.3	34.4	35.0	34.3	0.409	0.423	0.425	0.413

ϕ = Integrated number of 1 MeV $e \cdot cm^{-2}$

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Table 3.4-4. Average Temperature Coefficients of 2 and 10 ohm·cm Cells at 1 Solar Constant Intensity (Applicable for the Range from 13^{o} to $54^{o}C$ only)

		Before Irradiation				After 5.1×10^{15} 1 MeV $e \cdot cm^{-2}$			
10 ohm·cm Base Resistivity	Wafer Thickness (Inches)	0.012	0.0078	0.006	0.0037	0.012	0.0078	0.006	0.0037
	I_{sc} $\mu A/{}^{o}C$	85	83	63	68	156	141	148	129
	V_{oc} $mV/{}^{o}C$	1.80	2.12	1.90	2.12	2.04	2.12	2.17	2.26
2 ohm·cm Base Resistivity	Wafer Thickness (Inches)	0.0118	0.0071	0.0057	0.0034	0.0018	0.0071	0.0057	0.0034
	I_{sc} $\mu A/{}^{o}C$	80	54	92	75	129	63	100	129
	V_{oc} $mV/{}^{o}C$	1.90	2.12	2.09	2.21	1.97	2.19	2.12	2.07

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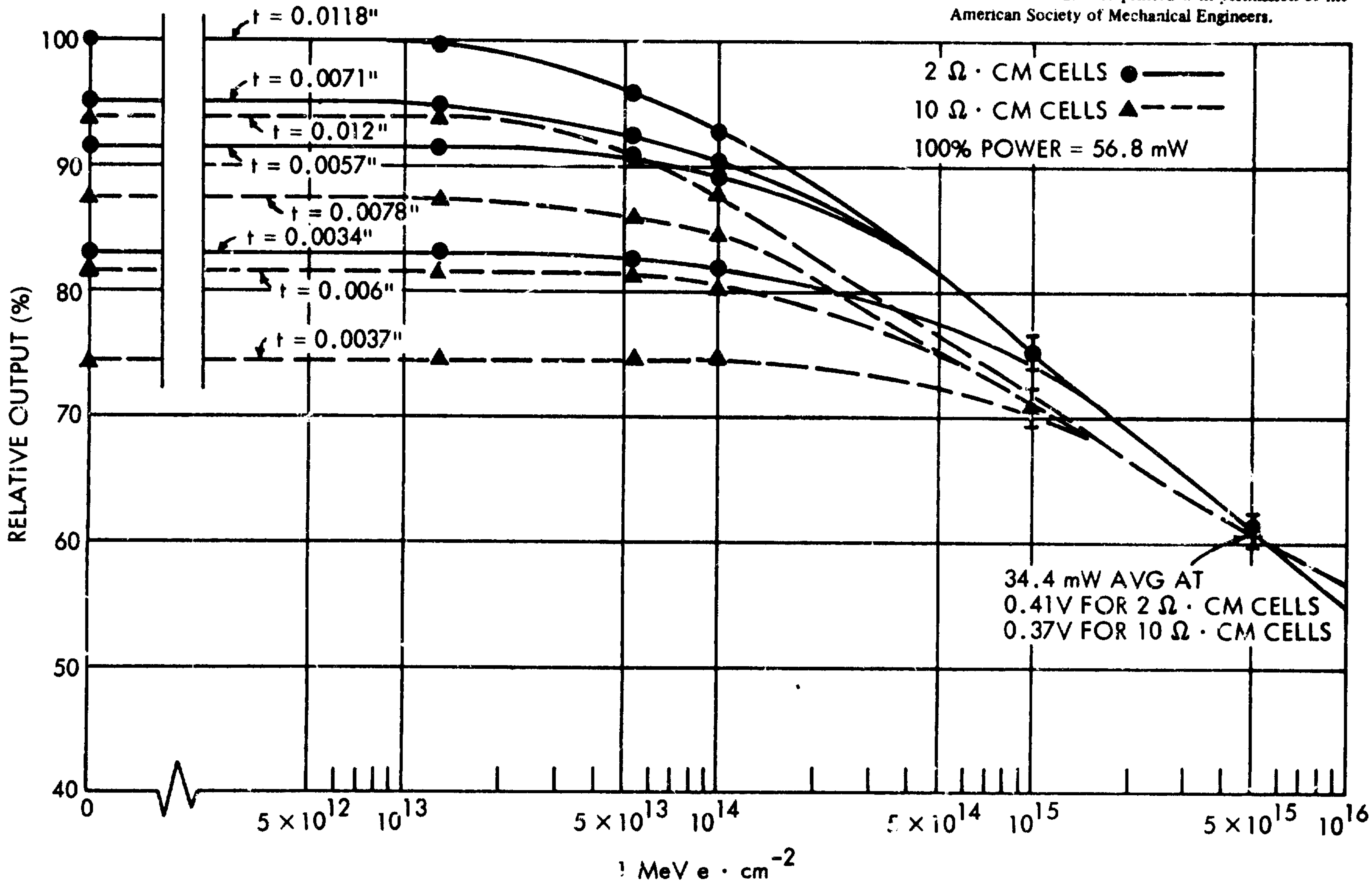

Figure 3.4-14. Maximum Power Output versus Fluence for 2 and 10 ohm · cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature

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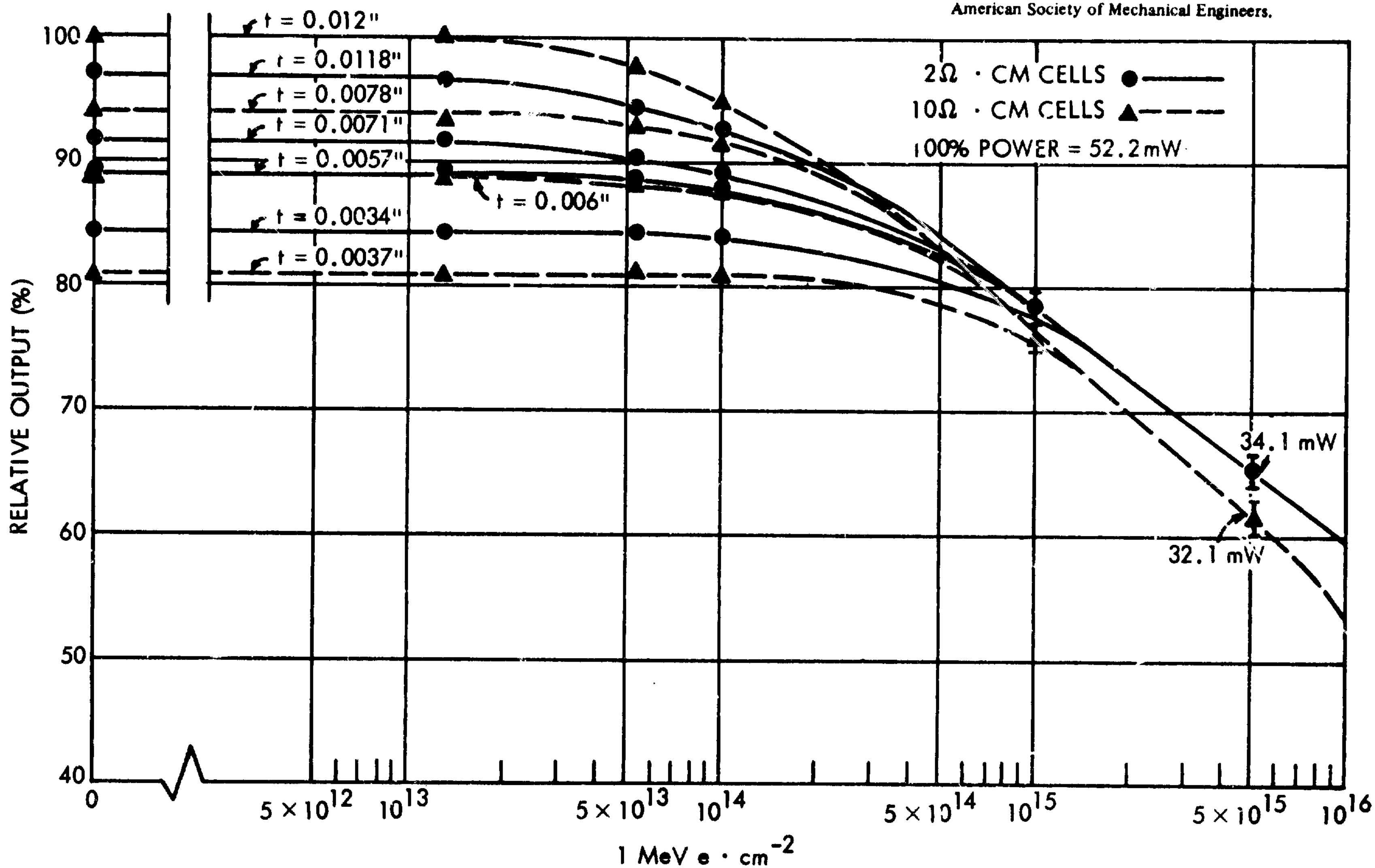

Figure 3.4-15. Power Output at 0.4 Volts versus Fluence for 2 and 10 ohm · cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature

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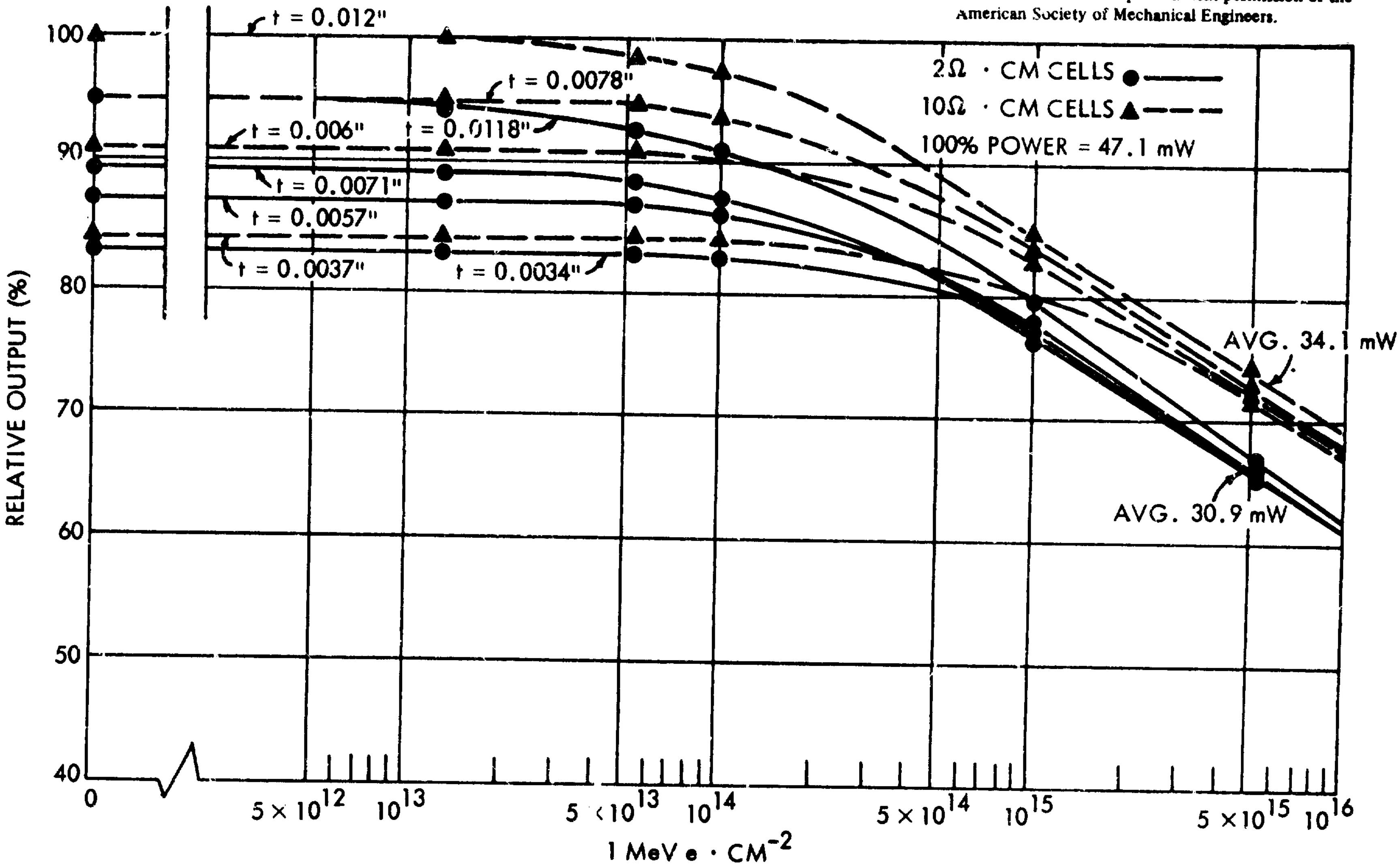

Figure 3.4-16. Power Output at 0.35 Volts versus Fluence for 2 and 10 ohm · cm Cells at 1 Solar Constant Intensity and at 27°C Cell Temperature

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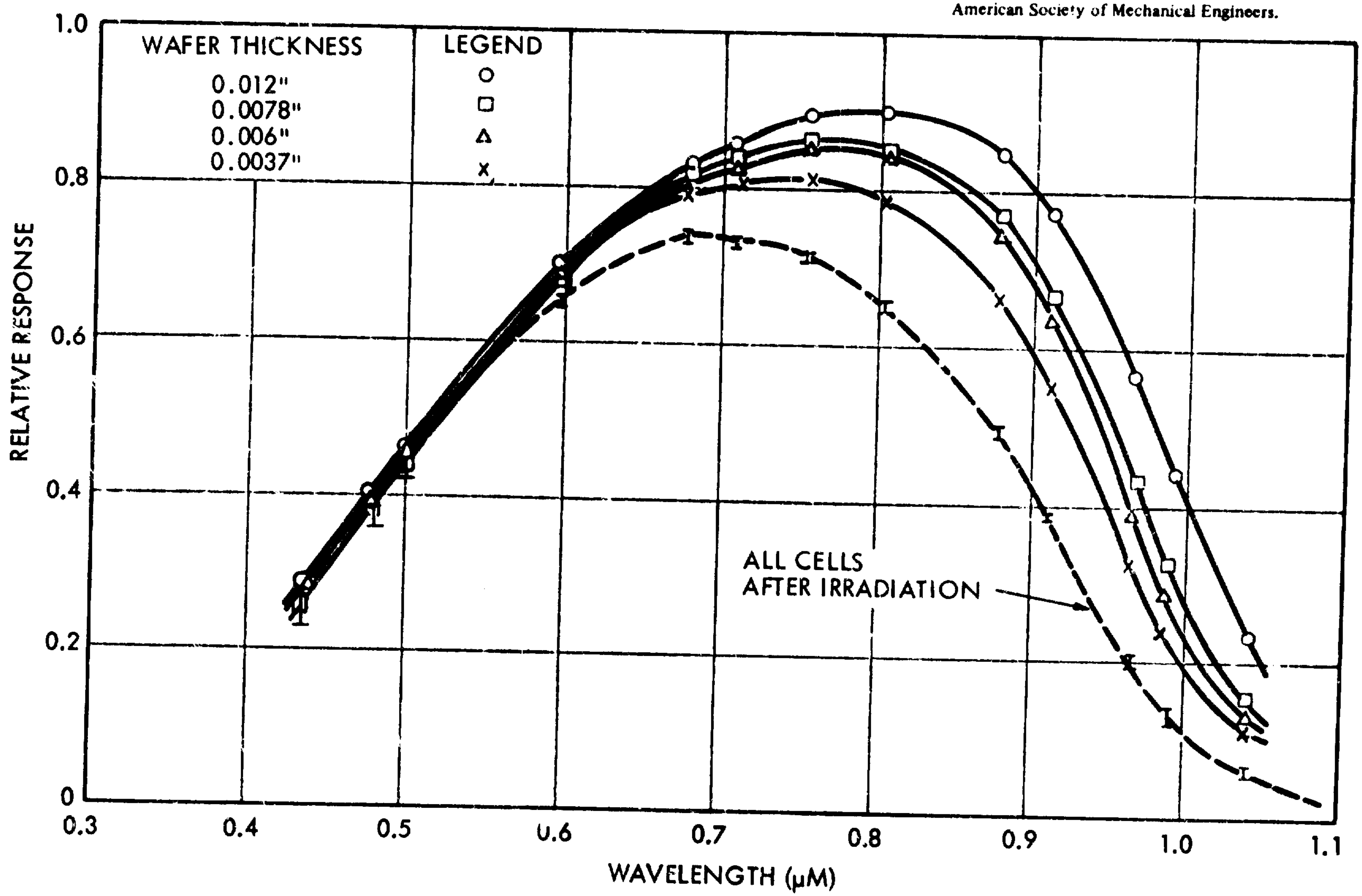

Figure 3.4-17. Spectral Response at 10 ohm · cm Cells Before and After Irradiation to 5.1×10^{15} 1-MeV Electrons per cm^2, at 25°C

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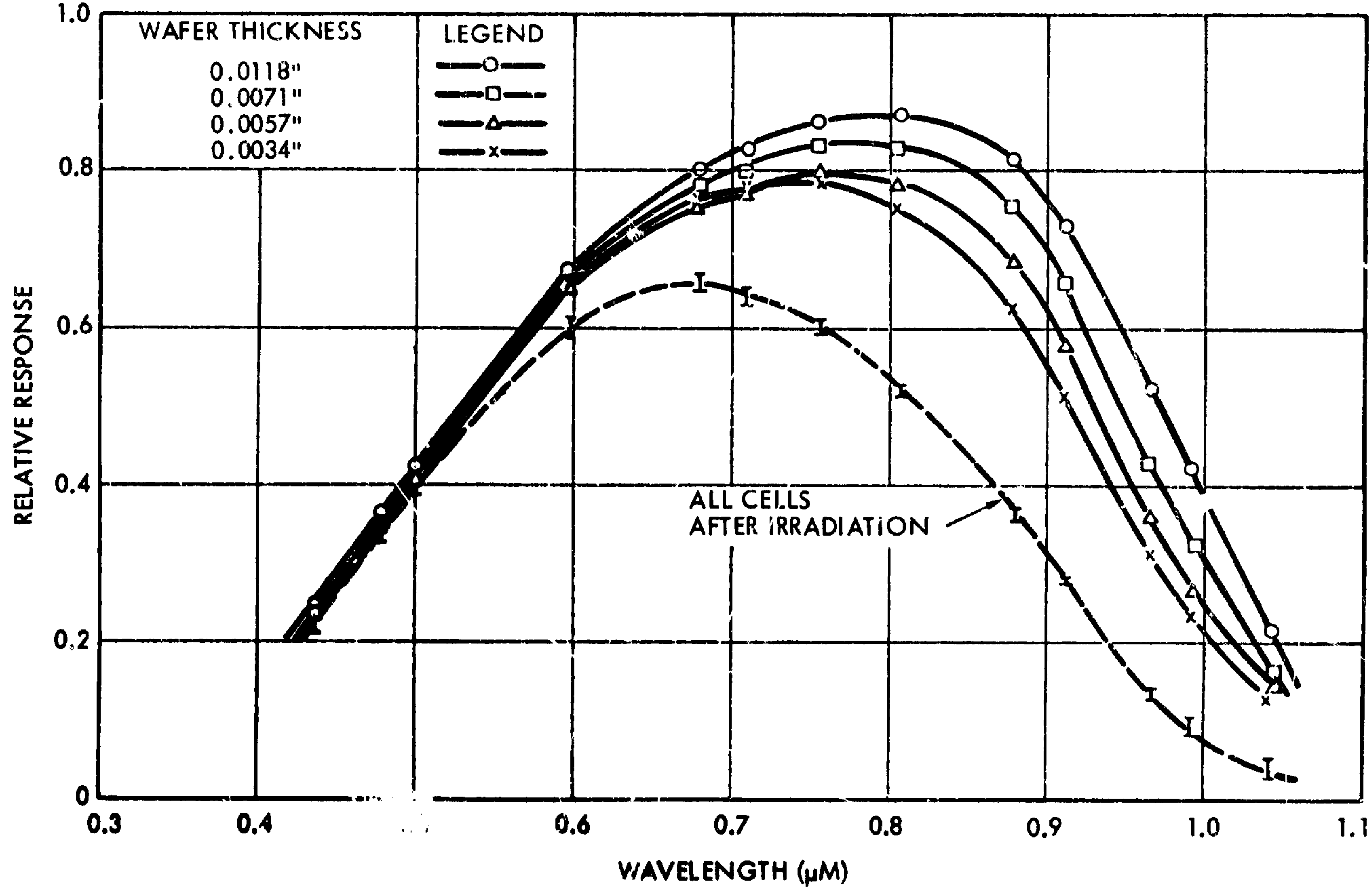


Figure 3.4-18 ... ponse of 2 ohm·cm Cells Before and After Irradiation to ... 1-MeV Electrons per cm^2, at 25°C

3.5 HIGH LIGHT INTENSITY - HIGH TEMPERATURE DATA

3.5.1 Performance of Conventional Silicon and Gallium-Arsenide Solar Cells (Ref. 3.5-1)

Cell Description

Cells: Per Table 3.5-1

Approximate Cell Manufacturing Date: Mid-1960's

Coating: SiO_x

Cover: None

Test Equipment

OCLI Model No. 2 Solar Simulator (AMO Spectrum)

Sun Gun, 625 watts, 3400°K (high-intensity light source, correlated to AM0 intensity at one solar constant)

Mineral Oil Bath, thermostatically controlled (optically clear oil controlled temperature of immersed cells during test)

Test Results

The test results are shown in the following figures.

3.5-1 Electrical Performance Parameters for Silicon Cells As a Function of Illumination Intensity

3.5-2 Current-Voltage Characteristics for Five-Grid, 10 ohm·cm Silicon Solar Cell at Temperatures from 30° to 150°C

3.5-3 Comparison of Current-Voltage Characteristics for Five-Grid and 13-Grid Cells at Two Temperatures at 2.8 $W \cdot cm^{-2}$ Illumination Intensity

3.5-4 Curve Factor for Two Types of Silicon Cells Versus Illumination Intensity

3.5-5 Electrical Performance Parameters for Seven-Grid Gallium-Arsenide Cells As a Function of Illumination Intensity Over a Range of Temperatures

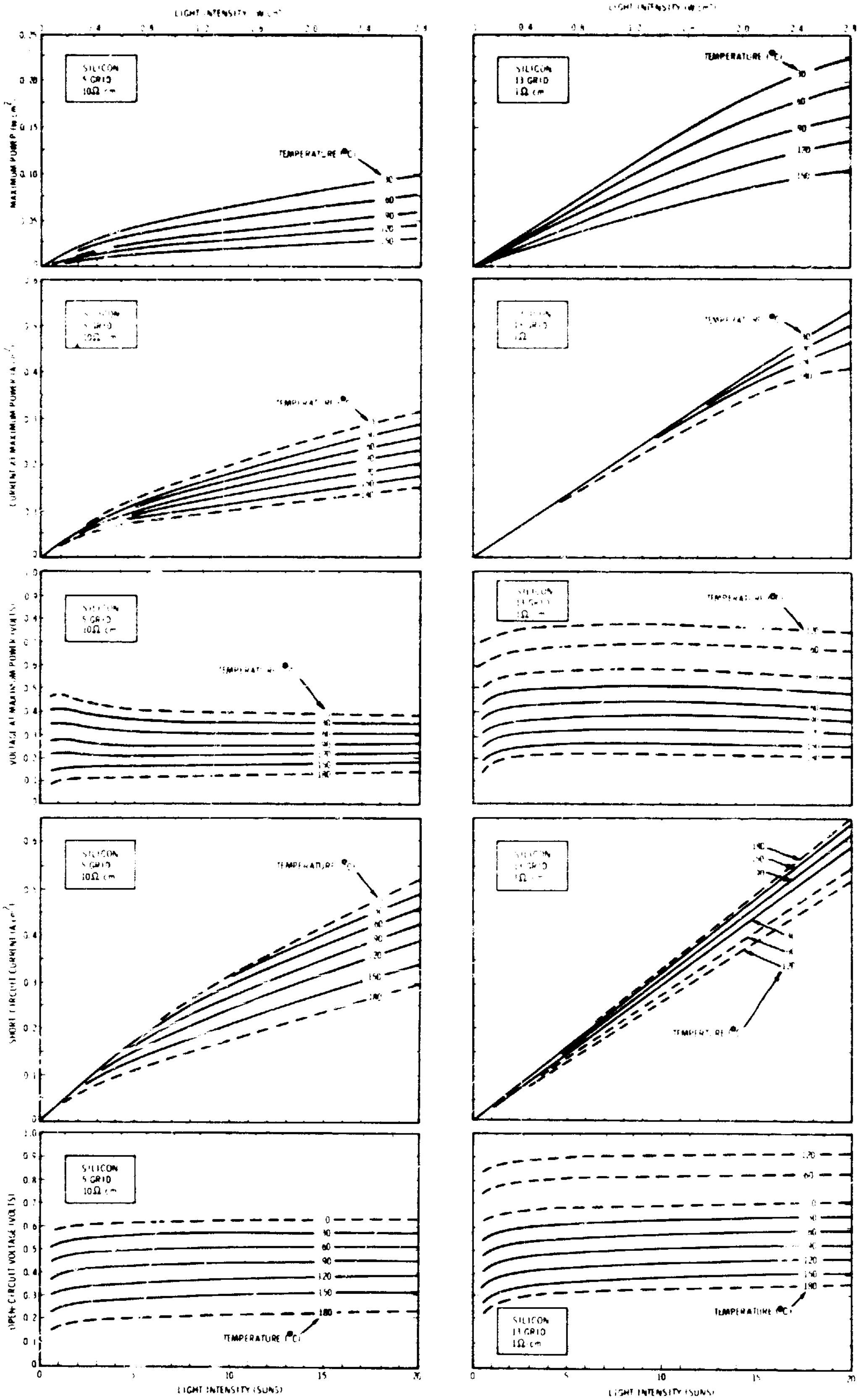
3.5-6 Open-Circuit Voltage for Three Cell Types as a Function of Temperature at 2.2 $W \cdot cm^{-2}$ Illumination Intensity

Table 3.5-1. Test Specimens

Type	Polarity	Manufac-turer*	No. of Cells	Material	Size (cm)	No. of Grids	Base Resistivity (ohm·cm)	Average Efficiency at 30°C at 0.14 $W \cdot cm^{-2}$ (%)	Contacts
1	N/P	H	4	Si	2 x 1	5	10	10.9	Ti-Ag, solder covered
	N/P	Hk	4	Si	2 x 1	5	10	10.9	Ti-Ag, solder covered
	N/P	RCA	4	Si	2 x 1	5	10	10.9	Ti-Ag, solder covered
	N/P	TI	4	Si	2 x 1	5	10	10.9	Ti-Ag, solder covered
2	N/P	Hk	3	Si	2 x 1	13	1	9.8	Electroless Ni, solder covered
3	P/N	RCA	1	GaAs	1 x 2	7	--	5.8	Solder covered

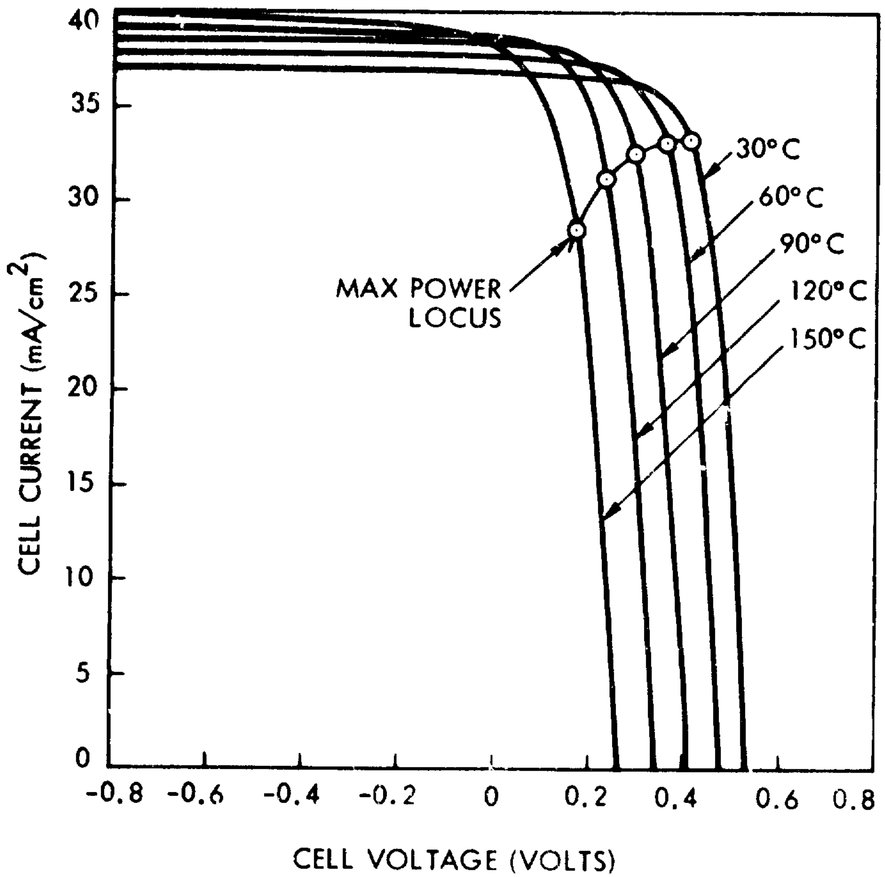
*H = Hoffman Electronics Corp.(now OCLI); Hk = Heliotek (now Spectrolab); RCA = Radio Corporation of America; TI = Texas Instrument Corporation

From Ref. 3.6-1.



(a) 5-grid, 10 ohm-cm cells. (b) 13-grid, 1 ohm-cm cells

Figure 3.5-1. Electrical Performance Parameters for Silicon Cells as a Function of Illumination Intensity



(a) At 0.14 W/cm^2 illumination intensity.

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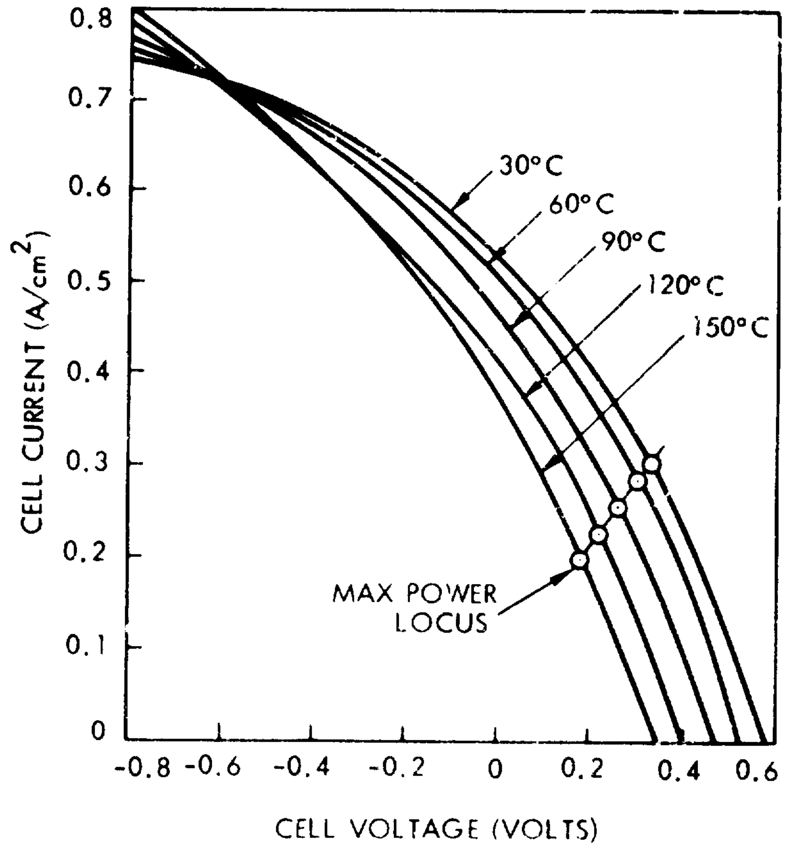

(b) At 2.8 W/cm^2 illumination intensity

Figure 3.5-2. Current-voltage Characteristics for Five-grid, 10 ohm · cm Silicon Solar Cell at Temperatures from 30° to 150°C

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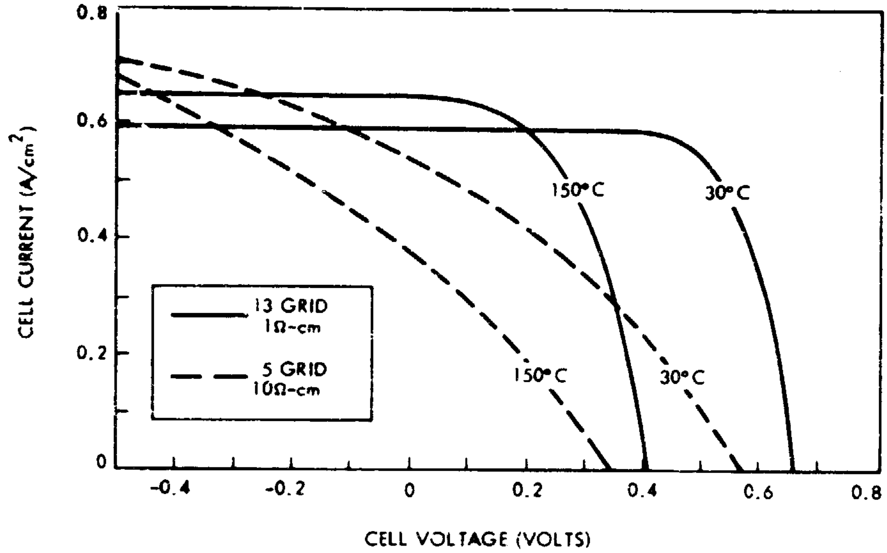

Figure 3.5-3. Comparison of Current-Voltage Characteristics for Five-Grid and 13-Grid Cells at Two Temperatures at 2.8 $W \cdot cm^{-2}$ Illumination Intensity

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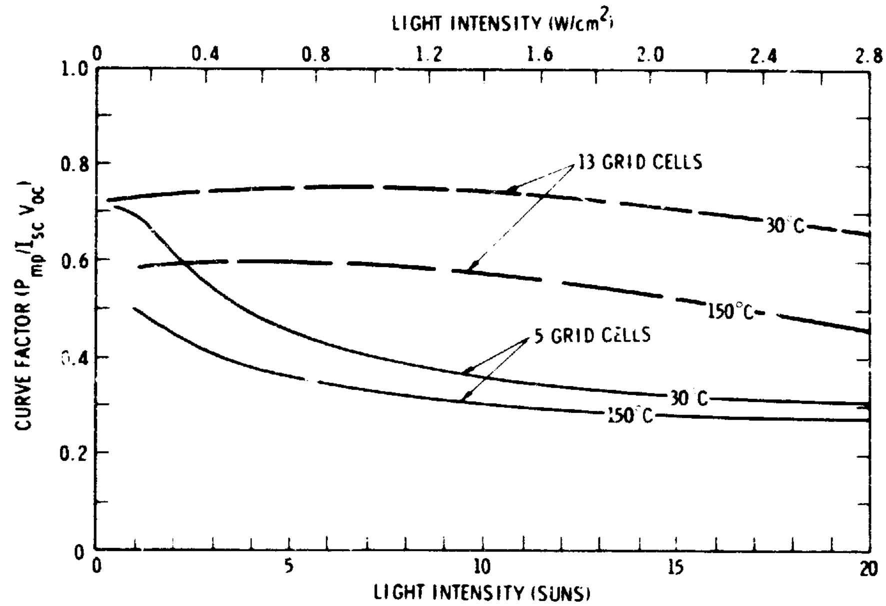

Figure 3.5-4. Curve Factor for Two Types of Silicon Cells Versus Illumination Intensity

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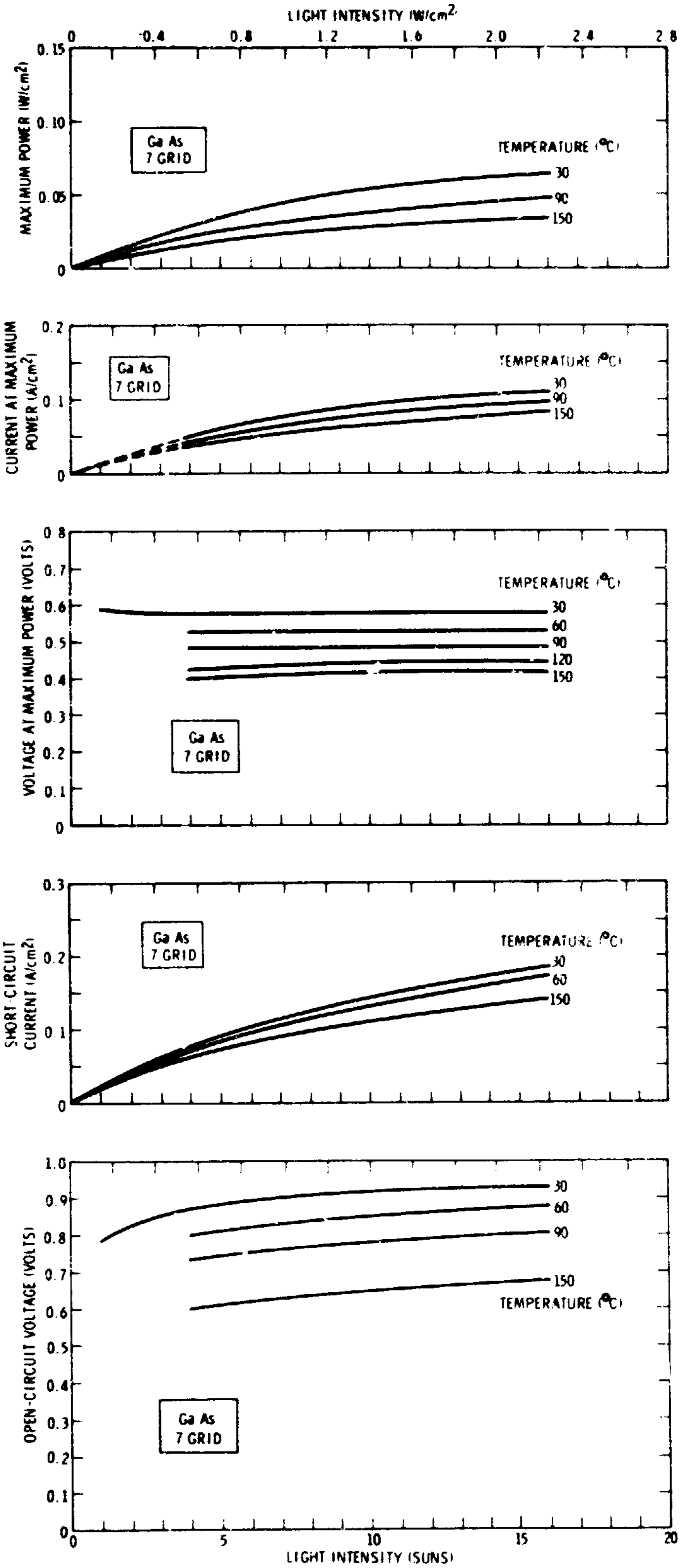

Figure 3.5-5. Electrical Performance Parameters for Seven-Grid Gallium Arsenide Cell as a Function of Illumination Intensity Over a Range of Temperature

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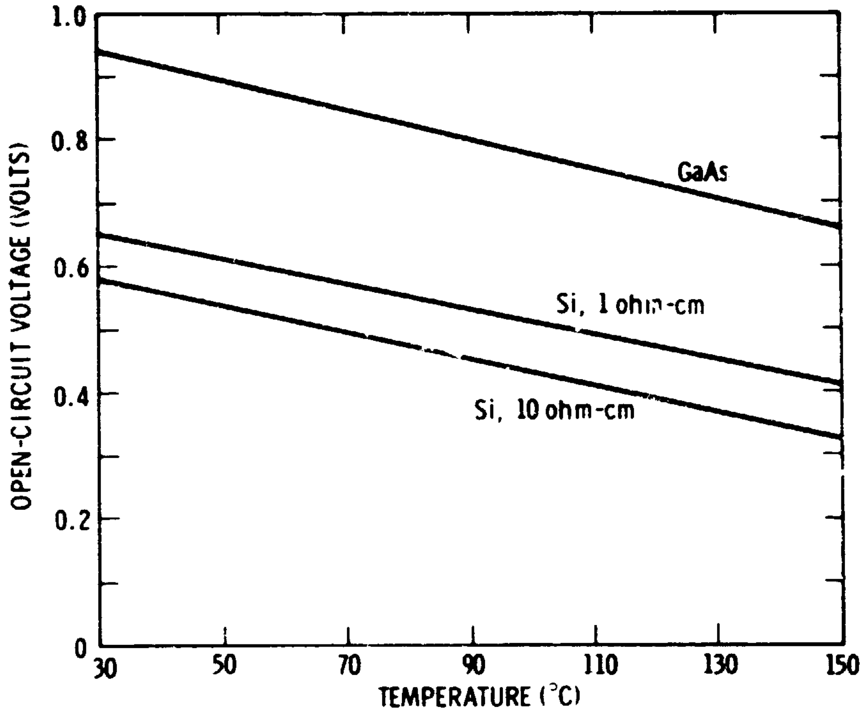

Figure 3.5-6. Open-Circuit Voltage for Three Cell Types as a Function of Temperature at 2.2 $W \cdot cm^{-2}$ Illumination Intensity

3.6 LOW TEMPERATURE - LOW INTENSITY DATA

3.6.1 Performance of Conventional Silicon Solar Cells (Ref. 3.6-1)

Cell Description

Cells: Per Table 3.6-1 (Conventional Cells)

Coating: SiO_x

Contacts: Ti-Ag

Test Equipment

Spectrolab X-25 Solar Simulator

Test Specimen Housing: Dry nitrogen-flushed, with quartz window, thermostatically controlled

Test Results

Test results are shown in the following table and figures:

Table 3.6-2	Cell Characteristics and Their Distribution Under Various Conditions for Four Cell Groups
Figure 3.6-1	Test Specimen Description
Figure 3.6-2	Cell Characteristics and Their Distribution Under Various Conditions for Four Cell Groups

Table 3.6-1. Test Specimen Description

Group	Quantity	Manufacturer	Base Resistance (ohm·cm)	Type	Size (cm^2)	Thickness (inch)	Solder	Contact
690218	100	CRL	10	N/P	4	0.010	Zone	Ti-Ag
690411	115	CRL	10	N/P	4	0.010	Zone	Ti-Ag
1-5	5	CRL	2	N/P	4	0.014	Yes	Ti-Ag
6-10	5	CRL	10	N/P	[illegible]	0.010	Zone	Ti-Ag
690321	115	HK	10	N/P	4	0.010	Yes	Ti-Ag
690414	35	TI	2	N/P	2	0.010	None	Ti-Ag
640504	4	RCA	2	N/P	2	0.015	None	Ti-Ag
640114	3	CRL	10	N/P	2	0.025	Yes	Ni

From Ref. 3.6-1.

CRL: Centralab, HK: Heliotek, TI: Texas Instrument,
RCA: Radio Corporation of America

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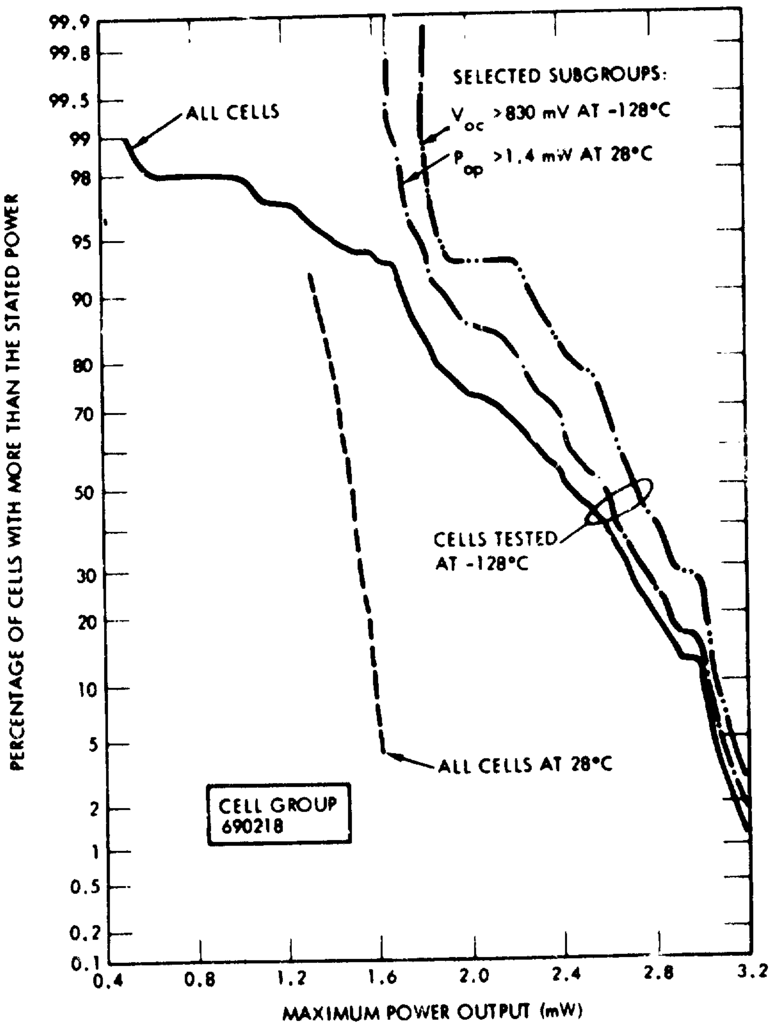

Figure 3.6-1. Test Specimen Description

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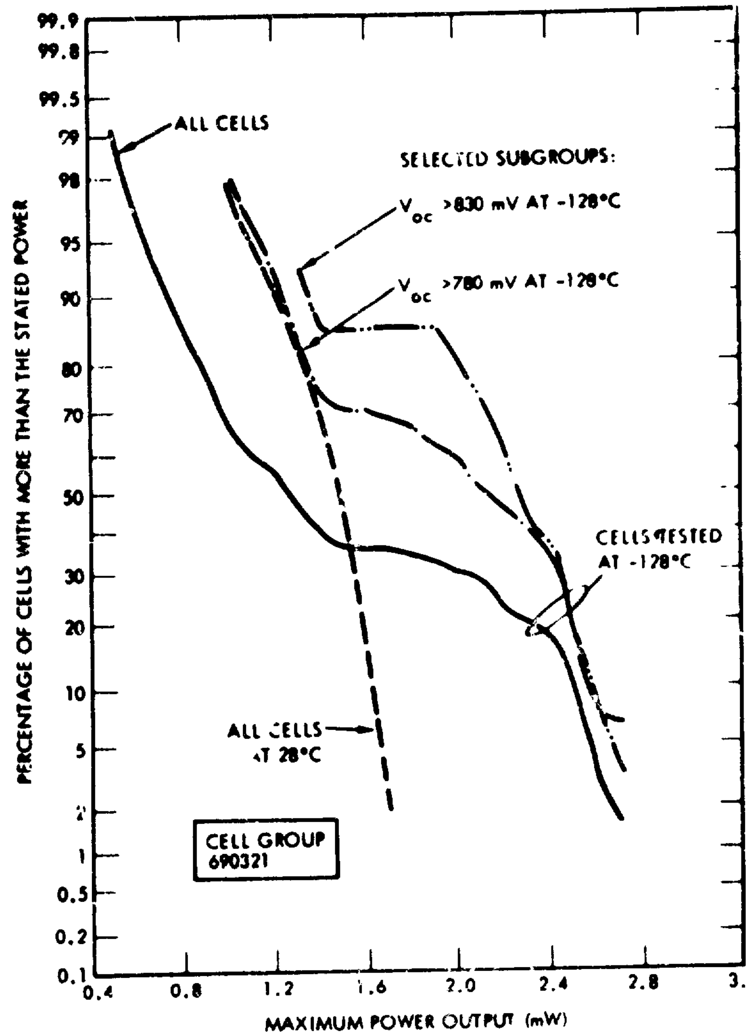

Figure 3.6-2. Cell Characteristics and Their Distribution Under Various Conditions for Four Cell Groups

Table 3.6-2. Cell Characteristics and Their Distribution Under Various Conditions for Four Cell Groups

Cell Mfg.	Cell Lot	Light Intensity ($mW \cdot cm^{-2}$)	Temperature (°C)	Minimum P_{op} at 28°C at 5 $mW \cdot cm^{-2}$ (mW)	Minimum V_{oc} at -128°C at 5.16 $mW \cdot cm^{-2}$ (mV)	Fraction of all Cells (%)	P_{op} Mean (mW)	P_{op} Sigma (mW)	P_{op} Sigma (%)
CRL	690218 100 Cells	140	28	None	None	100	56.7	4.73	8.3
		5	28	None	None	100	1.45	0.144	9.9
		5	28	1.3	None	92	1.48	0.077	5.2
		5	28	1.4	None	76	1.50	0.058	3.9
		5	-128	None	None	100	2.34	0.545	23.3
		5	-128	1.3	None	92	2.41	0.450	18.7
		5	-128	1.3	830	44	2.69	0.338	12.5
		5	-128	1.4	None	76	2.52	0.391	15.5
	690411 115 Cells	5.16	28	None	None	100	1.35	0.2	15
		5.16	-128	None	None	100	1.92	0.6	31
		5.16	-128	None	830	27	2.58	0.42	16
HK	690321 115 Cells	5.16	28	None	None	100	1.45	0.17	12
		5.16	-128	None	None	100	1.48	0.68	46
		5.16	-128	None	780	49	1.99	0.54	27
		5.16	-128	None	800	37	2.04	0.51	25
		5.16	-128	None	815	23	2.08	0.49	24
		5.16	-128	None	830	12	2.16	0.44	20
TI	690414 35 Cells	5	28	None	None	100	0.57	0.08	14
		5	-128	None	None	100	0.84	0.22	26

Table 3.6-2. Cell Characteristics and Their Distribution Under Various Conditions for Four Cell Groups (Continued)

Cell Mfg.	Cell Lot	I_{op} Mean (mA)	I_{op} Sigma (mA)	I_{op} Sigma (%)	V_{op} Mean (mV)	V_{op} Sigma (mV)	V_{op} Sigma (%)	I_{sc} Mean (mA)	I_{sc} Sigma (mA)	I_{sc} Sigma (%)	V_{oc} Mean (mV)	V_{oc} Sigma (mV)	V_{oc} Sigma (%)
CRL	690218 100 Cells	125.7	1.20	0.95	451	4.65	1.03	135.8	1.21	0.9	552	2.63	0.48
		4.06	0.262	6.4	356	19.1	5.4	4.82	0.053	1 1	443	40.9	9.2
		4.12	0.128	3.0	359	12.0	3.3	4.81	0.053	1.1	444	42.3	9.5
		4.15	0.101	2.4	363	9.13	2.5	4.81	0.055	1.1	445	46.4	10.4
		3.71	0.388	10.5	623	111	17.8	4.41	0.197	4.5	794	79.6	10.0
		3.74	0.322	8.6	641	85.3	13.3	4.40	0.198	4.5	808	48.5	6.0
		3.83	0.299	7.8	701	45.0	6.4	4.38	0.175	5.2	839	7.07	0.8
		3.77	0.313	8.3	665	66.0	9.9	4.40	0.195	4.4	822	30.9	3.8
	690411 115 Cells	4.03	0.35	8.7	334	23.5	7.0	4.94	0.2	4.0	441	10.5	2.4
		3.48	0.38	11	545	134	25	4.42	0.244	5.5	763	96	13
		3.72	0.40	11	692	55	8.0	4.41	0.244	5.5	844	12	1.4
HK	690321 115 Cells	4.17	0.36	8.6	347	16	4.6	5.04	0.14	2.8	447	8.5	1.9
		3.01	0.54	18	476	146	31	4.23	0.20	4.8	747	97	13
		3.30	0.54	16	593	83	14	4.21	0.20	4.8	816	22	2.7
		3.34	0.49	15	604	80	13	4.18	0.19	4.5	825	17	2.1
		3.33	0.49	15	616	70	11	4.17	0.22	5.3	835	13	1.6
		3.37	0.46	14	637	60	9.4	4.17	0.22	5.3	845	10	1.1
TI	690414 35 Cells	1.98	0.186	9.4	286	20.1	7.0	2.50	0.125	5.0	412	15.8	3.9
		1.89	0.14	7.4	442	103	23	2.32	0.11	4.8	676	101	15.0

From Ref. 3.6-1.

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3.1-7 F. C. Treble, "An Advanced Lightweight Solar Array," Solar Cells, Gordon and Breach Science Publishers, 1971.

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CHAPTER 7

MATERIAL PROPERTIES

CONTENTS

CHAPTER 7

MATERIAL PROPERTIES

7.1 CONVERSION FACTORS AND FORMULAS

The following data is included in this section:

- Table 7.1-1. Temperature Conversion
- Table 7.1-2. Addition of Mass per Unit Power
- Table 7.1-3. Addition of Power per Unit Mass
- Table 7.1-4. Conversion Factors — Solar Cell Array Units
- Table 7.1-5. Conversion Factors — Electrical
- Table 7.1-6. Conversion Factors — Thermal
- Table 7.1-7 Conversion Factors — Physical
- Table 7.1-8 Conversion Factors — Mass
- Table 7.1-9 Conversion Factors — Magnetic

Table 7.1-1. Temperature Conversion

Celsius to kelvin: $T_K = T_C + 273.15$

Farenheit to kelvin: $T_K = (5/9)\,(T_F + 459.67)$

Rankine to kelvin: $T_K = (5/9)\,T_R$

Farenheit to celsius: $T_C = (5/9)\,(T_F - 32)$

^oK	^oC	^oF	^oR
0	-273	-460	0
73	-200	-328	132
173	-100	-148	312
233	-40	-40	420
273	0	32	492
373	100	212	672

ΔT

^oF or ^oR	^oC or ^oK
1.8	1
1	0.5556

Table 7.1-2. Addition of Mass Per Unit Power

The total system's mass per unit power is

$$M_s = \sum_{i=1}^{n} m_i = m_1 + m_2 + \ldots + m_n \qquad (\mathrm{kg/W})$$

The m_i are the masses per unit power of the components

$$m_i = \frac{M_j}{P} \qquad (\mathrm{kg/W})$$

and M_i are the masses of the components and P is the power of the total system.

<u>Illustrative Example:</u>

Power Output:	600W
Solar Cells:	20 kg
Solar Cell Covers:	15 kg
Substrate:	25 kg

$$M_s = \frac{20}{600} + \frac{15}{600} + \frac{25}{600} = 0.10 \ \mathrm{kg/W}$$

Table 7.1-3. Addition of Power Per Unit Mass

The total system's power per unit mass, P, is calculated from:

$$\frac{1}{P} = \sum_{i=1}^{n} \frac{1}{p_i} = \frac{1}{p_1} + \frac{1}{p_2} + \ldots + \frac{1}{p_n} \qquad \left(\frac{1}{W/kg}\right)$$

The p_i are the power outputs per unit mass of the components

$$p_i = \frac{P}{m_i} \qquad (W/kg)$$

and P is the total system's power output and m_i are the masses of the components.

<u>Illustrative Example:</u>

Power Output:	600 W
Solar Cells:	20 kg P_c = 600/20 = 30 W/kg
Solar Cell Covers:	15 kg P_g = 600/15 = 40 W/kg
Substrate:	25 kg P_s = 600/25 = 24 W/kg

$$\frac{1}{P} = \frac{1}{30} + \frac{1}{40} + \frac{1}{24} = 0.0333 + 0.0250 + 0.0417 = 0.10$$

$$P = 1/0.10 = 10 \text{ W/kg}$$

Table 7.1-4. Conversion Factors — Solar Cell Array Units

To Convert From	Into	Do	This	By
W/kg	W/lb	Multiply	W/kg	0.45359
	kg/kW	Divide	1000	W/kg
	lb/kW	Divide	2204.6	W/kg
W/lb	W/kg	Multiply	W/lb	2.2046
	kg/kW	Divide	453.59	W/lb
	lb/kW	Divide	1000	W/lb
kg/kW	lb/kW	Multiply	kg/kW	2.2046
	W/kg	Divide	1000	kg/kw
	W/lb	Divide	453.59	kg/kW
lb/kW	kg/kW	Multiply	lb/kW	0.45359
	W/kg	Divide	2204.6	lb/kW
	W/lb	Divide	1000	lb/kW

Table 7.1-5. Conversion Factors — Electrical (Ref 7.1-1)

To Convert From	Multiply By	To Obtain
ohm•m	100	ohm•cm
μohm•cm	10^{-6}	ohm•cm
ohm•inch	2.54	ohm•cm
circular mils	0.7854	square mils
circular mils	5.067×10^{-6}	cm^2
circular mils/foot	1.662×10^{-7}	cm
ohm•circular mils/foot	1.662×10^{-7}	ohm•cm

Table 7.1-6. Conversion Factors — Thermal (Ref 7.1-2)

HEAT AND SOLAR FLUX

$kW \cdot m^{-2}$	$mW \cdot cm^{-2}$	$cal \cdot sec^{-1} \cdot cm^{-2}$	$Btu \cdot h^{-1}\ ft^{-2}$
1	100	0.0239	317.3
0.01	1	2.39^{-4}	3.173
41.83	4.183^{3}	1	1.327^{4}
3.15^{-4}	3.15^{-2}	7.53^{-5}	1

POWER

hp	kW	$ft \cdot lb \cdot s^{-1}$	$Btu \cdot h^{-1}$	$cal \cdot s^{-1}$	$MeV \cdot s^{-1}$
1	0.7457	550	2,547	178.2	4.65^{15}
1.341	1	737.6	3,415	239	6.24^{15}
1.818^{-3}	1.356^{-3}	1	4.63	0.324	8.46^{12}
2.546	1.899	1,400	6,480	453.9	1.18^{16}
3.93^{-4}	2.93^{-4}	0.216	1	0.070	1.82^{12}
5.61^{-3}	4.18^{-3}	3.088	14.29	1	2.61^{13}
2.15^{-16}	1.60^{-16}	1.118^{-13}	5.47^{-13}	3.83^{-14}	1

ENERGY

$kW \cdot h$	Btu	$ft \cdot lb$	cal	MeV	erg
1	3413	2.66^{6}	8.60^{5}	2.24^{19}	3.6^{13}
5.27^{-4}	1.8	1,400.6	453.6	1.18^{16}	1.9^{10}
2.93^{-4}	1	778.1	252	6.58^{15}	1.06^{10}
3.77^{7}	1.29^{-3}	1	0.324	8.46^{12}	1.36^{7}
1.16^{-6}	3.97^{-3}	3.087	1	2.61^{13}	4.19^{7}
4.46^{-20}	1.52^{-16}	1.18^{-13}	3.83^{-14}	1	1.60^{-6}
2.78^{-14}	9.48^{-11}	7.38^{-8}	2.39^{-8}	6.23^{5}	1

Note: Exponents indicate powers of 10.

Table 7. 1-6. Conversion Factors -- Thermal (Ref. 7. 1-2)
(Continued)

THERMAL CONDUCTIVITY

$cal \cdot s^{-1} \cdot cm \cdot cm^{-2} \cdot {}^{o}C^{-1}$	$Btu \cdot h^{-1} \cdot ft \cdot ft^{-2} \cdot {}^{o}F^{-1}$	$Btu \cdot h^{-1} \cdot ft \cdot in^{-2} \cdot {}^{o}F^{-1}$	$W \cdot cm \cdot cm^{-2} \cdot {}^{o}C^{-1}$
1	241.9	2,903	4.183
4.13^{-3}	1	12	0.0173
3.45^{-4}	0.0833	1	1.44^{-3}
0.239	57.8	694	1

HEAT TRANSFER COEFFICIENT

$watts \cdot cm^{-2} \cdot {}^{o}C^{-1}$	$cal \cdot s^{-1} \cdot cm^{-2} \cdot {}^{o}C^{-1}$	$Btu \cdot h^{-1} \cdot ft^{-2} \cdot {}^{o}F^{-1}$
1	0.239	1,763
4.183	1	7,373
5.67^{-4}	1.36^{-4}	1

Note: Exponents indicate powers of 10.

Table 7.1-7. Conversion Factors – Physical (Ref. 7.1-2)

LENGTH

cm	in.	ft	mi	nm	km
1	3.937^{-1}	3.28^{-2}			
2.54	1	8.33^{-2}			
30.48	12	1			
		5280	1	8.685^{-1}	1.6093
		6080	1.1515	1	1.8531
		3281	6.214^{-1}	5.396^{-1}	1

VOLUME

cm^3	ft^3	liter	yd^3	gallon
1	3.531^{-5}	1.0^{-3}	1.308^{6}	2.642^{-4}
2.832^{4}	1	28.32	3.704^{-2}	7.481
10^{3}	3.531^{-2}	1	1.308^{-3}	2.642^{-1}
7.646^{5}	27	7.646^{2}	1	202
3.785^{3}	1.337^{-1}	3.785	4.951^{-3}	1

AREA

cm^2	in^2	ft^2
1	0.155	1.08^{-3}
6.45	1	6.94^{-3}
929	144	1

DENSITY

g/cm^3	lb/ft^3
1	62.43
0.016	1

VELOCITY

cm/s	ft/s	ft/h	mi/h
1	0.0328	118.1	0.0224
30.48	1	3,600	0.6818
8.47^{-3}	2.78^{-4}	1	1.89^{-4}
44.70	1.467	5,280	1

TIME
(BASED ON 24-HOUR DAY, 30-DAY MONTH, 12-MONTH YEAR)

s	min	h	day	week	mo	yr
1						
60	1					
3.6^{3}	60	1				
8.64^{4}	1.44^{3}	24	1			
6.05^{5}	1.01^{4}	168	7	1		
2.59^{6}	4.32^{4}	720	30	4.29	1	
3.11^{7}	5.18^{5}	8.64^{3}	360	51.4	12	1

PRESSURE

torr	mm Hg	micron (μ Hg)	Pa	$N \cdot m^{-2}$
1	1	1^{-3}	133.322	133.322
7.501^{-3}	7.501^{-3}	7.501	1	1

MASS

See Table 7.1-8

Note: Exponents indicate powers of 10.

Table 7.1-8. Conversion Factors — Mass

To Convert From	Multiply by	To Obtain
gram	10^{-3}	kilogram
lbm (pound mass)	0.4536	kilogram
ounce mass (avoirdupois)	0.02835	kilogram
slug	14.59	kilogram
gram/centimeter^3	10^{-3}	kilogram/meter^3
lbm/inch^3	27,680	kilogram/meter^3
lbm/ft^3	16.02	kilogram/meter^3
ounce mass/inch^3	1730	kilogram/meter^3
slug/ft^3	515.4	kilogram/meter^3
dyne	10^{-5}	newton
kilogram force	9.807	newton
kilopound force	9.807	newton
kip	4,448	newton
lbf (pound force)	4.448	newton
ounce force	0.2780	newton
poundal	0.1383	newton

Table 7.1-9. Conversion Factors — Magnetic

To Convert From	Multiply by	To Obtain
<u>Magnetic Dipole Moments</u>		
amp·turn·ft^2	6.86×10^{-6}	ft·lb/gauss
amp·turn·m^2	10.76	amp·turn·ft^2
pole·cm	1.00×10^{-3}	amp·turn·m^2
pole·cm	10.76×10^{-3}	amp·turn·ft^2
pole·cm	7.38×10^{-8}	ft·lb/gauss
weber·meter	$1.00 \times 10^{7}/4\pi$	amp·turn·m^2
weber·meter	$1.00 \times 10^{10}/4\pi$	pole·cm
<u>Magnetic Fields</u>		
gamma	1.00×10^{-9}	tesla
gauss	1.00×10^{-4}	tesla
gilbert	$10/4\pi$	ampere·turn
lines	1.00×10^{-8}	weber
maxwell	1.00×10^{-8}	weber
oersted	$1000/4\pi$	ampere·turn/meter
tesla	1.00	newton/(amp·turn·meter)
unit pole	1.2566×10^{-7}	weber
weber	1.00	volt·second
weber amp	1.00	joule
weber/m^2	1.00	tesla

7.2 PHYSICAL CONSTANTS

The following data is included in this section:

- Table 7.2-1. Names and Symbols of SI Units
- Table 7.2-2. SI Prefixes
- Table 7.2-3. Values of Important Constants
- Table 7.2-4. Values of Physical Constants
- Table 7.2-5. Periodic Chart of Elements
- Table 7.2-6. Greek Alphabet

Table 7.2-1. Names and Symbols of SI* Units (Ref. 7.2-1)

Quantity	*Name of Unit*	*Symbol*	
	SI BASE UNITS		
length	meter	m	
mass	kilogram	kg	
time	second	s	
electric current	ampere	A	
thermodynamic temperature	kelvin	K	
luminous intensity	candela	cd	
amount of substance	mole	mol	
	SI DERIVED UNITS		
area	square meter	m^2	
volume	cubic meter	m^3	
frequency	hertz	Hz	s^{-1}
mass density (density)	kilogram per cubic meter	kg/m^3	
speed, velocity	meter per second	m/s	
angular velocity	radian per second	rad/s	
acceleration	meter per second squared	m/s^2	
angular acceleration	radian per second squared	rad/s^2	
force	newton	N	$kg \cdot m/s^2$
pressure (mechanical stress)	pascal	Pa	N/m^2
kinematic viscosity	square meter per second	m^2/s	
dynamic viscosity	newton-second per square meter	$N \cdot s/m^2$	
work, energy, quantity of heat	joule	J	$N \cdot m$
power	watt	W	J/s
quantity of electricity	coulomb	C	$A \cdot s$
potential difference, electromotive force	volt	V	W/A
electric field strength	volt per meter	V/m	
electric resistance	ohm	Ω	V/A
capacitance	farad	F	$A \cdot s/V$
magnetic flux	weber	Wb	$V \cdot s$
inductance	henry	H	$V \cdot s/A$
magnetic flux density	tesla	T	Wb/m^2
magnetic field strength	ampere per meter	A/m	
magnetomotive force	ampere	A	
luminous flux	lumen	lm	$cd \cdot sr$
luminance	candela per square meter	cd/m^2	
illuminance	lux	lx	lm/m^2
wave number	1 per meter	m^{-1}	
entropy	joule per kelvin	J/K	
specific heat capacity	joule per kilogram kelvin	$J/(kg \cdot K)$	
thermal conductivity	watt per meter kelvin	$W/(m \cdot K)$	
radiant intensity	watt per steradian	W/sr	
activity (of a radioactive source)	1 per second	s^{-1}	
	SI SUPPLEMENTARY UNITS		
plane angle	radian	rad	
solid angle	steradian	sr	

*Systeme International d'Unités; The International System of Units.

Table 7. 2-2. SI Prefixes

Factor by which unit is multiplied	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Table 7. 2-3. Values of Important Constants (Ref. 7. 2-1)

$\pi = 3.141\ 592\ 653\ 589$

$e = 2.718\ 281\ 828\ 459$

$\mu_0 = 4\pi \times 10^{-7}$ H/m (exact), permeability of free space

$= 1.256\ 637\ 061 \times 10^{-6}$ H/m

$\epsilon_0 = \mu_0^{-1} c^{-2}$ F/m, permittivity of free space

$= 8.854\ 185 \times 10^{-12}$ F/m

Table 7.2-4. Values of Physical Constants (Ref. 7.2-1)

Quantity	Symbol	Value	Error ppm	Prefix	Unit
Speed of light in vacuum	c	2.997 925 0	0.33	$\times 10^{8}$	m s^{-1}
Gravitational constant	G	6.673 2	460	10^{-11}	N m^{2} kg^{-2}
Avogadro constant	N_A	6.022 169	6.6	10^{26}	kmol^{-1}
Boltzmann constant	k	1.380 622	43	10^{-23}	J K^{-1}
Gas constant	R	8.314 34	42	10^{3}	J kmol^{-1} K^{-1}
Volume of ideal gas, standard conditions	V_0	2.241 36	-------	10^{1}	m^{3} kmol^{-1}
Faraday constant	F	9.648 670	5.5	10^{7}	C kmol^{-1}
Unified atomic mass unit	u	1.660 531	6.6	10^{-27}	kg
Planck constant	h	6.626 196	7.6	10^{-34}	J s
	$h/2\pi$	1.054 591 9	7.6	10^{-34}	J s
Electron charge	e	1.602 191 7	4.4	10^{-19}	C
Electron rest mass	m_e	9.109 558	6.0	10^{-31}	kg
		5.485 930	6.2	10^{-4}	u
Proton rest mass	m_p	1.672 614	6.6	10^{-27}	kg
		1.007 276 61	0.08	-------	u
Neutron rest mass	m_n	1.674 920	6.6	10^{-27}	kg
		1.008 665 20	0.10	-------	u
Electron charge to mass ratio	e/m_e	1.758 802 8	3.1	10^{11}	C kg^{-1}
Stefan-Boltzmann constant	σ	5.669 61	170	10^{-8}	W m^{-2} K^{-4}
First radiation constant	$2\pi hc^2$	3.741 844	7.6	10^{-16}	W m^{2}
Second radiation constant	hc/k	1.438 833	43	10^{-2}	m K
Rydberg constant	R_∞	1.097 373 12	0.10	10^{7}	m^{-1}
Fine structure constant	α	7.297 351	1.5	10^{-3}	
	α^{-1}	1.370 360 2	1.5	10^{+2}	
Bohr radius	a_0	5.291 771 5	1.5	10^{-11}	m
Classical electron radius	r_e	2.817 939	4.6	10^{-15}	m
Compton wavelength of electron	λ_C	2.426 309 6	3.1	10^{-12}	m
	$\lambda_C/2\pi$	3.861 592	3.1	10^{-13}	m
Compton wavelength of proton	$\lambda_{C,p}$	1.321 440 9	6.8	10^{-15}	m
	$\lambda_{C,p}/2\pi$	2.103 139	6.8	10^{-16}	m
Compton wavelength of neutron	$\lambda_{C,n}$	1.319 621 7	6.8	10^{-15}	m
	$\lambda_{C,n}/2\pi$	2.100 243	6.8	10^{-16}	m
Electron magnetic moment	μ_e	9.284 851	7.0	10^{-24}	J T^{-1}
Proton magnetic moment	μ_p	1.410 620 3	7.0	10^{-26}	J T^{-1}
Bohr magneton	μ_B	9.274 096	7.0	10^{-24}	J T^{-1}
Nuclear magneton	μ_n	5.050 951	10	10^{-27}	J T^{-1}
Gyromagnetic ratio of protons in H_2O	γ'_p	2.675 127 0	3.1	10^{8}	rad s^{-1} T^{-1}
	$\gamma'_p/2\pi$	4.257 597	3.1	10^{7}	Hz T^{-1}
Gyromagnetic ratio of protons in H_2O corrected for diamagnetism of H_2O.	γ_p	2.675 196 5	3.1	10^{8}	rad s^{-1} T^{-1}
	$\gamma_p/2\pi$	4.257 707	3.1	10^{7}	Hz T^{-1}
Magnetic flux quantum	Φ_0	2.067 853 8	3.3	10^{-15}	Wb
Quantum of circulation	$h/2m_e$	3.636 947	3.1	10^{-4}	J s kg^{-1}
	h/m_e	7.273 894	3.1	10^{-4}	J s kg^{-1}

Table 7.2-5. Periodic Chart of Elements (Ref. 7.2-2)

(Used by permission of the Chemical Rubber Co.)

Period	1a	2a	3b	4b	5b	6b	7b	8	8	8	1b	2b	3a	4a	5a	6a	7a	0	Orbit
I 2 Elements	1 H 1.00797																	2 He 4.0026	K
II 8 Elements	3 Li 6.939	4 Be 9.0122	Transition Elements										5 B 10.811	6 C 12.01115	7 N 14.0067	8 O 15.9994	9 F 18.9984	10 Ne 20.183	K–L
III 8 Elements	11 Na 22.9898	12 Mg 24.[illegible]						Group 8					13 Al 26.9815	14 Si 28.086	15 P 30.9738	16 S 32.064	17 Cl 35.453	18 Ar 39.948	K–L–M
IV 18 Elements	19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.90	23 V 50.942	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.9216	34 Se 78.96	35 Br 79.909	36 Kr 83.80	–L–M–N
V 18 Elements	37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.905	46 Pd 106.4	47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.9044	54 Xe 131.30	–M–N–O
VI 32 Elements	55 Cs 132.905	56 Ba 137.34	57* La 138.91	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)	–N–O–P
VII	87 Fr (223)	88 Ra (226)	89** Ac (227)																–O–P–Q

*Lanthanides	58 Ce 140.12	59 Pr 140.907	60 Nd 144.24	61 Pm (145)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.924	66 Dy 162.50	67 Ho 164.930	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 174.97	–N–O–P
**Actinides	90 Th 232.038	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (245)	97 Bk (249)	98 Cf (249)	99 Es (254)	100 Fm (252)	101 Md (256)	102 No (254)	103 Lw	–O–P–Q

Numbers in parentheses are mass numbers of most stable isotope of that element.

KEY TO CHART

Atomic Number (black)	50
Symbol (black)	Sn
Atomic Weight (red)	118.69
Oxidation States (green)	
Electron Configuration (blue)	

Table 7.2-6. Greek Alphabet

alpha	α	A	nu	ν	N
beta	β β	B	xi	ξ	Ξ
gamma	γ	Γ	omicron	o	O
delta	δ	Δ	pi	π	Π
epsilon	ϵ	E	rho	ρ	P
zeta	ζ	Z	sigma	σ ς	Σ
eta	η	H	tau	τ	T
theta	θ ϑ	Θ Θ	upsilon	υ	Υ
iota	ι	I	phi	ϕ φ	Φ
kappa	κ	K	chi	χ	X
lambda	λ	Λ	psi	ψ	Ψ
mu	μ	M	omega	ω	Ω

7.3 MASS, DENSITY AND WEIGHT

The following data is included in this section.

- Table 7.3-1 Densities of Several Metals
- Table 7.3-2 Densities of Several Nonmetals
- Table 7.3-3 Densities of Several Polymers, Adhesives, Primers, Sealants and Resins
- Table 7.3-4 Mass of Solar Cells
- Table 7.3-5 Mass of Various Array Parts

The data in this section were obtained from the following sources:

- Handbook of Chemistry and Physics, 13th Edition, Chemical Rubber Publishing Company, 1948
- Jet Propulsion Laboratory previously unpublished data.
- NASA SP-7012, "The International System of Units," 2nd revision, 1973.
- "Reference Data for Radio Engineers, 4th Edition, International Telephone and Telegraph Corporation, 1957.
- Supplier catalogs and brochures included elsewhere in this handbook.
- TRW Systems Group previously unpublished data.

Table 7.3-1. Densities of Several Metals

Material	Density ($g \cdot cm^{-3}$)
Aluminum	2.70
Beryllium	1.85
Brass	8.47
Copper, annealed	8.89
Copper, hard-drawn	8.94
Gold	18.90-19.32
Indium	7.28-7.30
Invar	8.05
Iron, pure	7.86
Kovar	8.2
Lead	11.34
Magnesium	1.74
Molybdenum	10.2
Nickel	8.9
Palladium	11.4-12.0
Phosphor-Bronze (4Sn, 0.5P, Cu)	8.9
Platinum	21.4
Silver	10.5
Steel	7.8-7.9
Tin	7.3
Titanium	4.5
Tungsten	18.6-19.3
Zinc	7.14
Zirconium	6.4

Table 7.3-2. Densities of Several Nonmetals

Material	Density ($g \cdot cm^{-3}$)
Ceria-Doped Microsheet	2.62
FEP Teflon	2.1-2.2
Fused Silica	2.202
Germanium	5.46
Kapton	1.42
Korad	1.17
Microsheet	2.51
Silicon	2.32-2.40
TFE Teflon	2.1-2.2

Table 7.3-3. Densities of Several Polymers, Adhesives, Primers, Sealants and Resins (Cured)

Material	Manufacturer	Color	Density ($g \cdot cm^{-3}$)
6-1104	Dow Corning	White, translucent	1.12
93-500	Dow Corning	Clear	1.08
RTV-40	General Electric	White	1.35
RTV-41	General Electric	White	1.31
RTV-118	General Electric	Clear	1.04
RTV-511	General Electric	White	1.20
RTV-560	General Electric	Red	1.42
RTV-566	General Electric	Red	1.51
RTV-567	General Electric	Clear	1.00
RTV-577	General Electric	White	1.35
RTV-580	General Electric	Red	1.49
RTV-602	General Electric	Clear	0.995
Silgard 182	Dow Corning	Clear	1.05
Silgard 184	Dow Corning	Clear	1.08
R6-3488	Dow Corning	Clear	1.05
R6-3489	Dow Corning	Clear	1.02

Table 7.3-4. Mass of Solar Cells

Size (mm x mm)	Thickness (mm)	(in.)	Solder Coating	Mass (g)	Ref.
20.0 x 20.0	0.25	0.010	Thin	0.252	7.3-2
20.0 x 20.0	0.25	0.010	Medium	0.285	7.3-2
20.0 x 20.0	0.25	0.010	Thick	0.320	7.3-2
20 x 20	0.20	0.008	None	0.194	7.3-1
20 x 20	0.15	0.006	None	0.151	7.3-1
20 x 20	0.10	0.004	None	0.107	7.3-1

Table 7.3-5. Mass of Various Array Parts

Item	Material	Size (mm x mm x mm)	Mass (g)	Ref.
Cover Glass	Microsheet	20.2 x 19.2 x 0.15	0.140	7.3-2
Cover Glass	Fused Silica	20.2 x 19.2 x 0.32	0.310	7.3-2
Wire, Insulated	Copper	AWG No. 28, per meter	~1.4	7.3-2
Wire, Insulated	Copper	AWG No. 24, per meter	~3.0	7.3-2
Diode, Blocking	Glass Envelope	1 amp	0.275	7.3-2

7.4 CENTROIDS, MOMENTS OF INERTIA AND RADII OF GYRATION

The following data is included in this section:

- Figure 7.4-1 Centroids, Moments of Inertia, and Radii of Gyration of Some Common Solar Cell Array Configurations

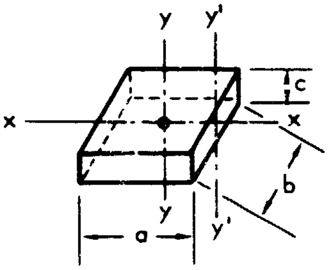
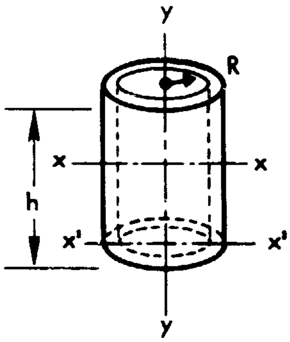
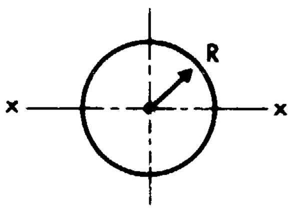
FIGURE	CENTROID	MOMENT OF INERTIA	RADIUS OF GYRATION
 FLAT PLATE	0	$I_x = \frac{m(b^2 + c^2)}{12}$ $I_y = \frac{m(a^2 + b^2)}{12}$ $I_y' = \frac{m(4a^2 + b^2)}{12}$	$k_x = \left(\frac{b^2 + c^2}{12}\right)^{1/2}$ $k_y = \left(\frac{a^2 + b^2}{12}\right)^{1/2}$ $k_y' = \left(\frac{4a^2 + b^2}{12}\right)^{1/2}$
 CYLINDRICAL SHELL	0	$I_x = \frac{m(6R^2 + h^2)}{12}$ $I_x' = \frac{m(3R^2 + 2h^2)}{6}$ $I_y = mR^2$	$k_x = \left(\frac{6R^2 + h^2}{12}\right)^{1/2}$ $k_x' = \left(\frac{3R^2 + 2h^2}{6}\right)^{1/2}$ $k_y = R$
 SPHERICAL SHELL	0	$I_x = \frac{2mR^2}{3}$	$k_x = R\left(\frac{2}{3}\right)^{1/2}$

Figure 7.4-1. Centroids, Moments of Inertia, and Radii of Gyration of Some Common Solar Cell Array Configurations (m = mass)

7.5 ELASTIC MODULUS, POISSON'S RATIO AND ULTIMATE STRENGTH OF METALS

The following data is included in this section:

- Figure 7.5-1 Kovar – Poisson's Ratio, Ultimate Strength and Young's Modulus
- Figure 7.5-2 Molybdenum – Poisson's Ratio, Ultimate Strength and Young's Modulus
- Figure 7.5-3 Palladium, Pure – Poisson's Ratio, Ultimate Strength and Young's Modulus
- Figure 7.5-4 Silver, Pure – Poisson's Ratio, Ultimate Strength and Young's Modulus
- Figure 7.5-5 Solder (62 Sn - 36 Pb - 2 Ag) – Poisson's Ratio, Ultimate Strength and Young's Modulus
- Figure 7.5-6 Elastic Moduli versus Temperature for Several Materials
- Figure 7.5-7 Invar – Variation of Mechanical Properties with Temperature
- Figure 7.5-8 Stress-Strain Curves for Invar
- Figure 7.5-9 Effect of Cold Work on the Room Temperature Properties of 0.23 cm Diameter Fine Silver Wire
- Figure 7.5-10 Influence of Low Temperatures on the Ultimate Strength of Annealed Silver
- Figure 7.5-11 Influence of Low Temperatures on the Fatigue Strength of Annealed Silver
- Figure 7.5-12 Effect of Low Temperatures on the Stress-Strain Behavior of Molybdenum

(Continued next page)

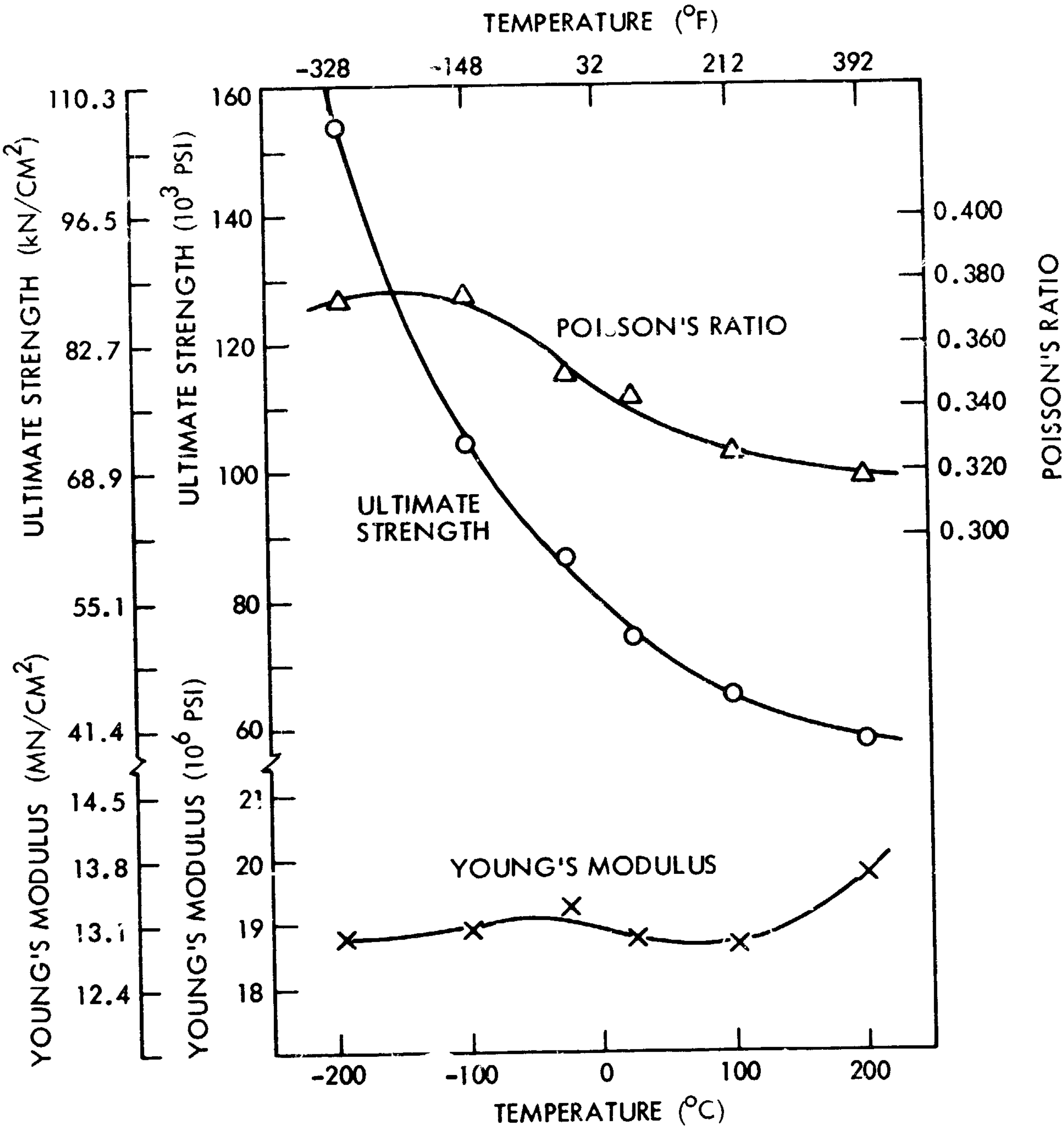


Figure 7.5-1. Kovar – Poisson's Ratio, Ultimate Strength and Young's Modulus (Ref 7.5-1)

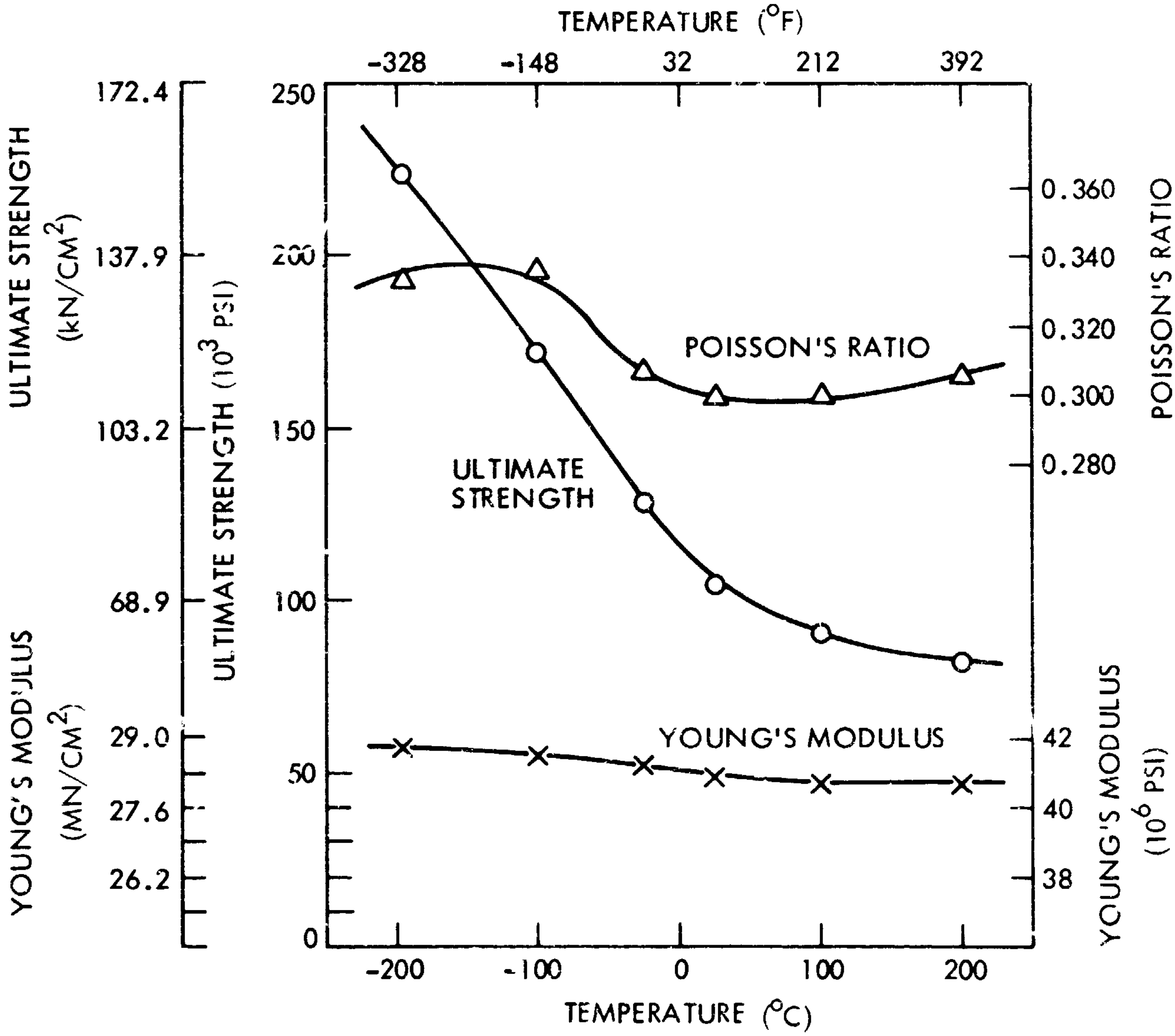


Figure 7.5-2. Molybdenum — Poisson's Ratio, Ultimate Strength and Young's Modulus (Ref 7.5-1)

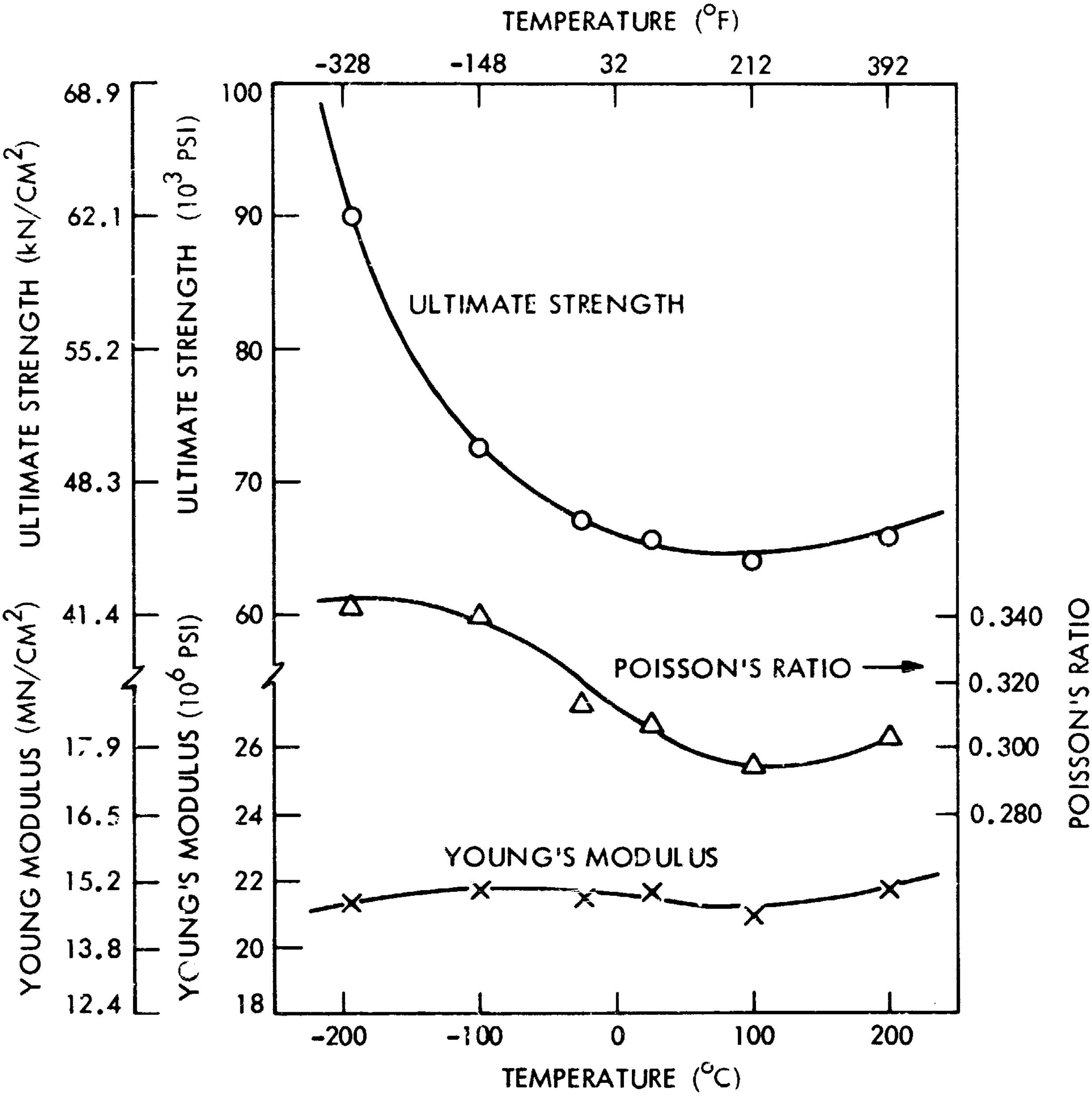


Figure 7.5-3. Palladium, Pure – Poisson's Ratio, Ultimate Strength and Young's Modulus (Ref 7.5-1)

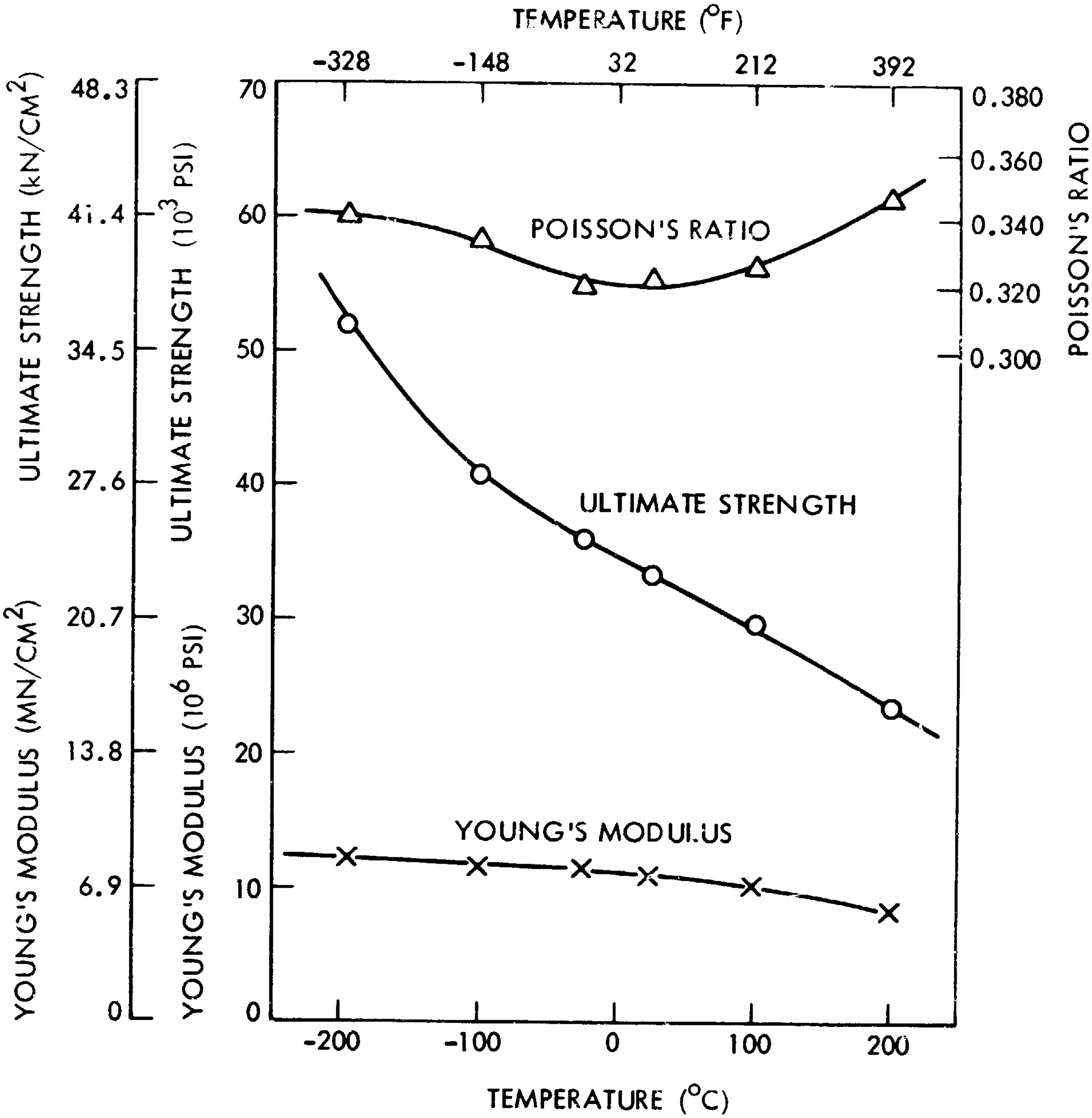


Figure 7.5-4. Silver, Pure — Poisson's Ratio, Ultimate Strength and Young's Modulus (Ref 7.5-1)

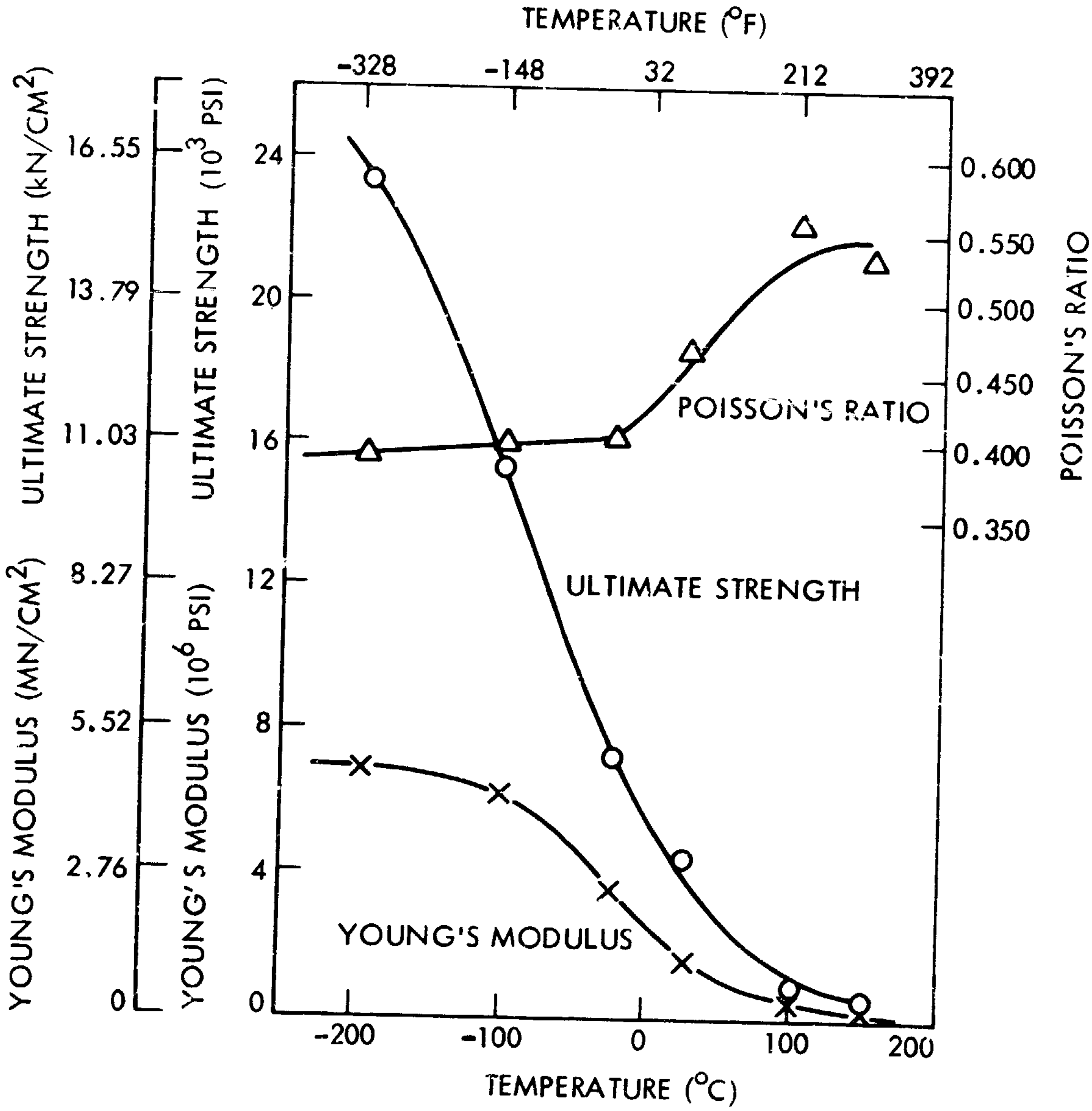


Figure 7.5-5. Solder (62 Sn-36 Pb-2 Ag) – Poisson's Ratio, Ultimate Strength and Young's Modulus (Ref 7.5-1)

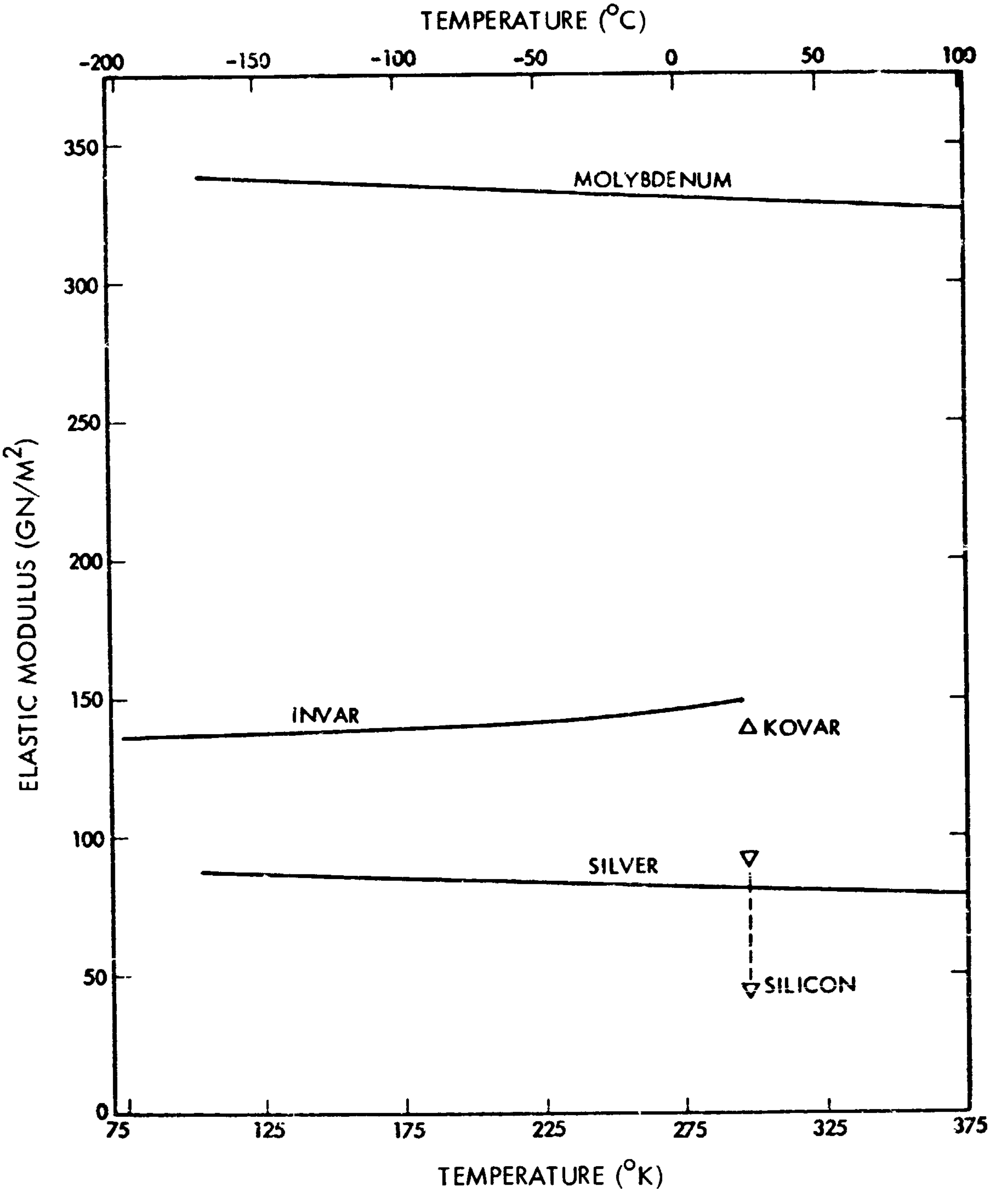


Figure 7.5-6. Elastic Moduli Versus Temperature for Several Materials (Summary Data)

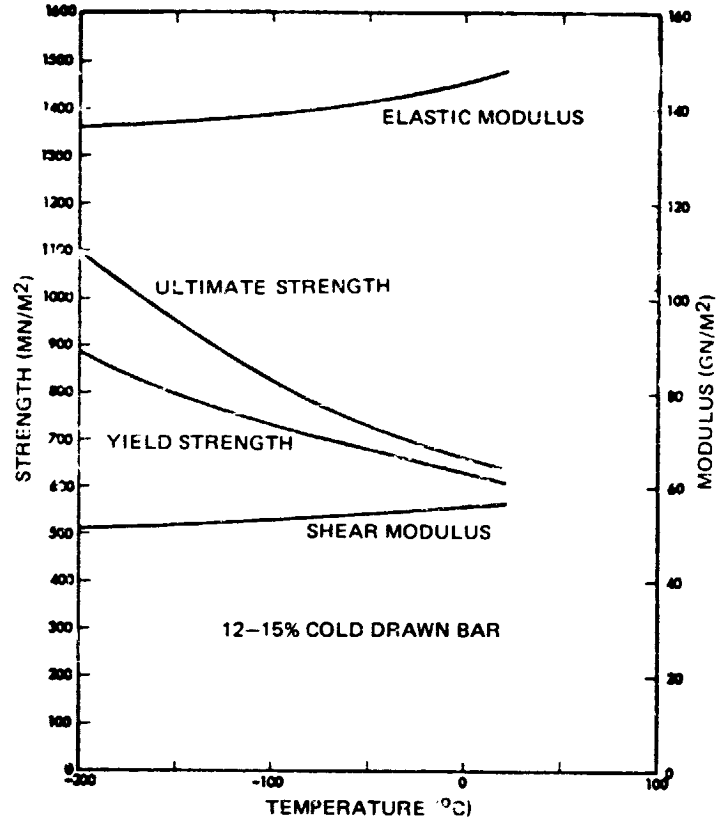


Figure 7. 5-7. Invar – Variation of Mechanical Properties with Temperature (Ref. 7. 5-7)

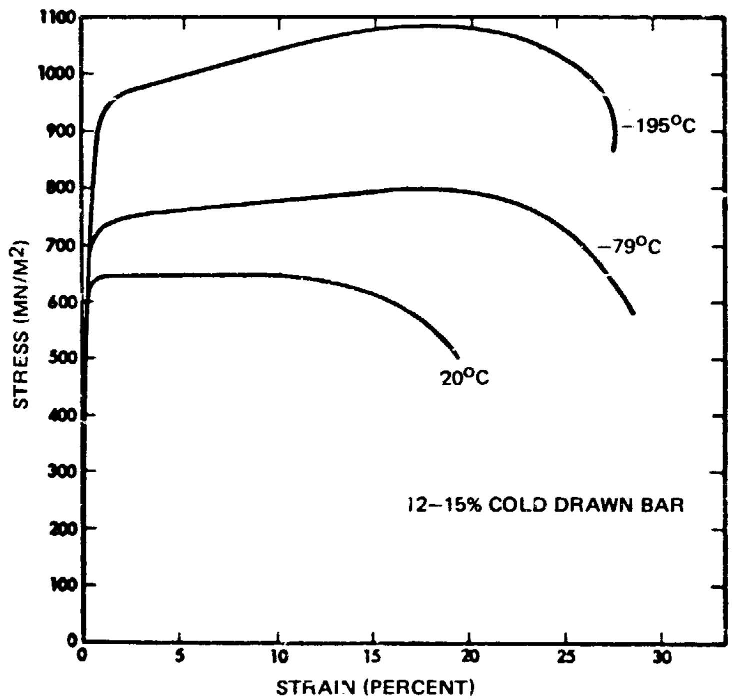


Figure 7. 5-8. Stress-Strain Curves for Invar (Ref. 7. 5-7)

From Ref. 7.5-12. Reprinted with permission of the Van Nostrand Reinhold Co.

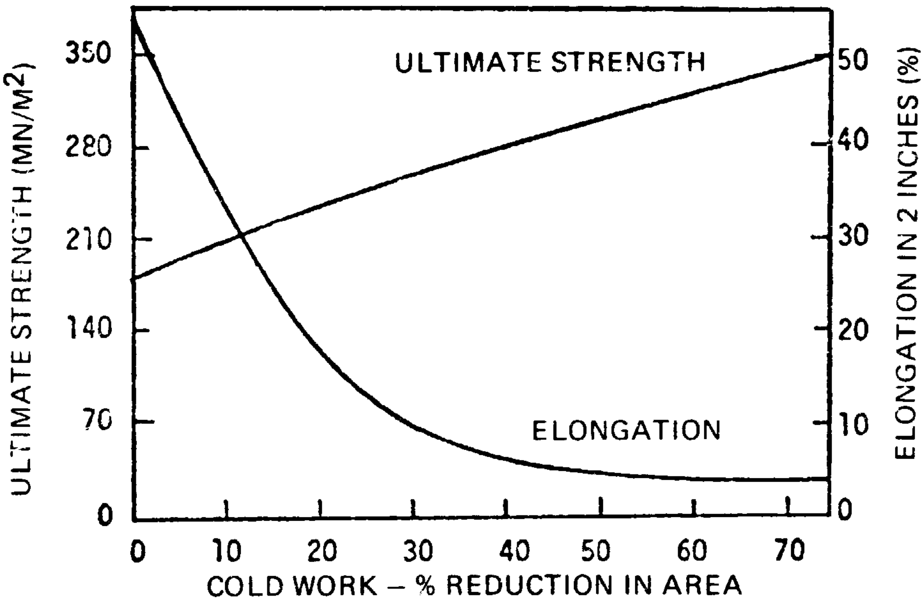


Figure 7.5-9. Effect of Cold Work on the Room Temperature Properties of 0.23 cm Diameter Fine Silver Wire (Ref. 7.5-12)

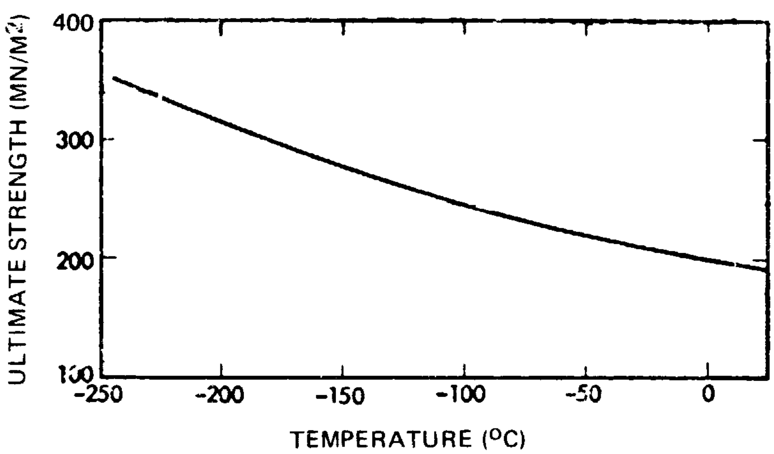


Figure 7.5-10. Influence of Low Temperatures on the Ultimate Strength of Annealed Silver (Ref. 7.5-14, Used by permission of the Royal Society)

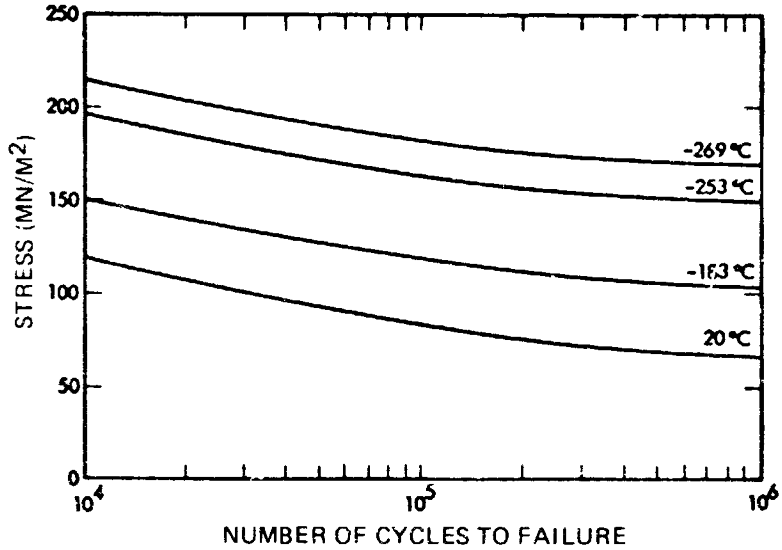


Figure 7.5-11. Influence of Low Temperatures on the Fatigue Strength of Annealed Silver (Ref. 7.5-14)

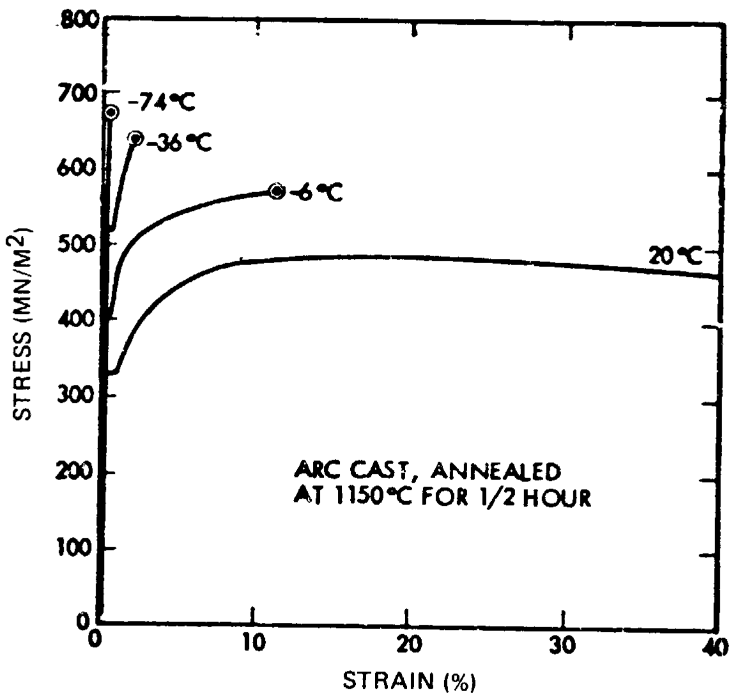


Figure 7.5-12. Effect of Low Temperatures on the Stress-Strain Behavior of Molybdenum (Ref. 7.5-14, Used by permission of the Royal Society)

Table 7.5-1. Strength of Kovar (Refs. 7.5-5 and 7.5-6)

T (°C)	5% Yield Strength (MN/m^2)	Ultimate Strength (MN/m^2)
21	410	535
213	270	405

Table 7.5-2. Elastic and Shear Moduli and Poisson's Ratio of Invar (Refs. 7.5-7 and 7.5-8)

T	E	G	Poisson's Ratio
°C	GN/m^2	GN/m^2	
-200	136	51.5	-
-100	139	53	-
25	145	56	0.29

Table 7.5-3. Strength of Invar (Ref. 7.5-9)

	Annealed	15% Cold Worked
Ultimate strength, MN/m^2	490	640
Yield strength, MN/m^2	270	450

Table 7.5-4. Elastic Modulus of Silver (Ref. 7.5-10)

T (°C)	Elastic Modulus, E (GN/m^2)
-170	87.3
-100	84.8
0	81.9
20	80.0
100	78.5

Table 7. 5-5. Elastic and Shear Moduli of Silver (Ref. 7. 5-11)

T	E		G***
(°C)	(GN/m^2*)	(GN/m^2**)	(GN/m^2)
20	70-80	--	--
27	--	--	26.8
30	--	72.8	--
100	78.4	--	--
127	--	70.3	--
130	--	--	26.0

*Annealed above 700°C after 5 percent work hardening per Raub
**Annealed per Addicks
***Annealed wire

Notes to Table 7. 5-5:

The elastic modulus is somewhat affected by cold working. Raub reports a 5 percent cold-worked silver to have E = 69.6 GN/m^2 at 20°C and Addicks reports hard-drawn wire to have E = 74.9 GN/m^2. The purity levels in the test materials, the complete mechanical working history, the degree of anisotropy and the grain size are not available in any of these cases. The most frequently used value determined with samples strained 5 percent and then annealed for 30 minutes at 350°C is 71 GN/m^2 at room temperature.

The shear modulus does not change greatly for hard-drawn stock; values from 26.9 to 30 GN/m^2 are reported depending on mechanical working history. A nominal value of Poisson's ratio is 0.37 for annealed material with an increase to 0.39 for hard-drawn material.

Table 7. 5-6. Strength of Silver (Ref. 7. 5-13)

Fine Silver Sheet (0. 81 mm thick)	Yield Strength (MN/m^2)	Ultimate Strength (MN/m^2)
Annealed (1/2 hour at 760°C)	54	155
Cold-Worked (50 percent reduction)	305	374

Table 7. 5-7. Elastic Modulus of Molybdenum (Ref. 7. 5-10)

T (°C)	E (GN/m^2)
-170	338
-100	335
0	331
20	320
100	326

Table 7. 5-8. Elastic and Shear Moduli and Poisson's Ratio of Molybdenum

T (°C)	Young's Modulus, E (GN/m^2)	Shear Modulus, G (GN/m^2)	Poisson's Ratio
25	320	120	0.324
100	310	117	0.328
500	280	110	0.315

Table 7. 5-9. Strength of Molybdenum

T (°C)	0.2% Yield Strength (MN/m^2)	Ultimate Strength (MN/m^2)
-75	1000	1040
-40	830	860
0	680	690
40	570	620
70	520	580

Notes to Table 7. 5-9:

At -75 degrees the reduction in area of sheet stock is zero, indicating brittle behavior. This is further emphasized by the stress strain curves of Figure 7. 5-12 which show an increase in strength with a reduction in temperature accompanied by a very rapid decrease in the elongation. However, Ref. 7. 5-16 indicates that the addition of 7 percent rhenium can lower the ductile to brittle transition temperature below -200°C.

7.6 ELASTIC MODULUS, POISSON'S RATIO AND ULTIMATE STRENGTH OF SILICON AND GLASS

The following data is included in this section:

- Figure 7.6-1. Single-crystal Silicon – Elastic Modulus
- Figure 7.6-2. Single-crystal Silicon – Poisson's Ratio
- Figure 7.6-3. Fused Silica (Corning Glass 7940) – Elastic Modulus, Poisson's Ratio and Shear Modulus
- Table 7.6-1. Ultimate Strength for Single-crystal Silicon Tensile Specimens
- Table 7.6-2 Ultimate Strength for Single-Crystal Silicon Compressive Specimens

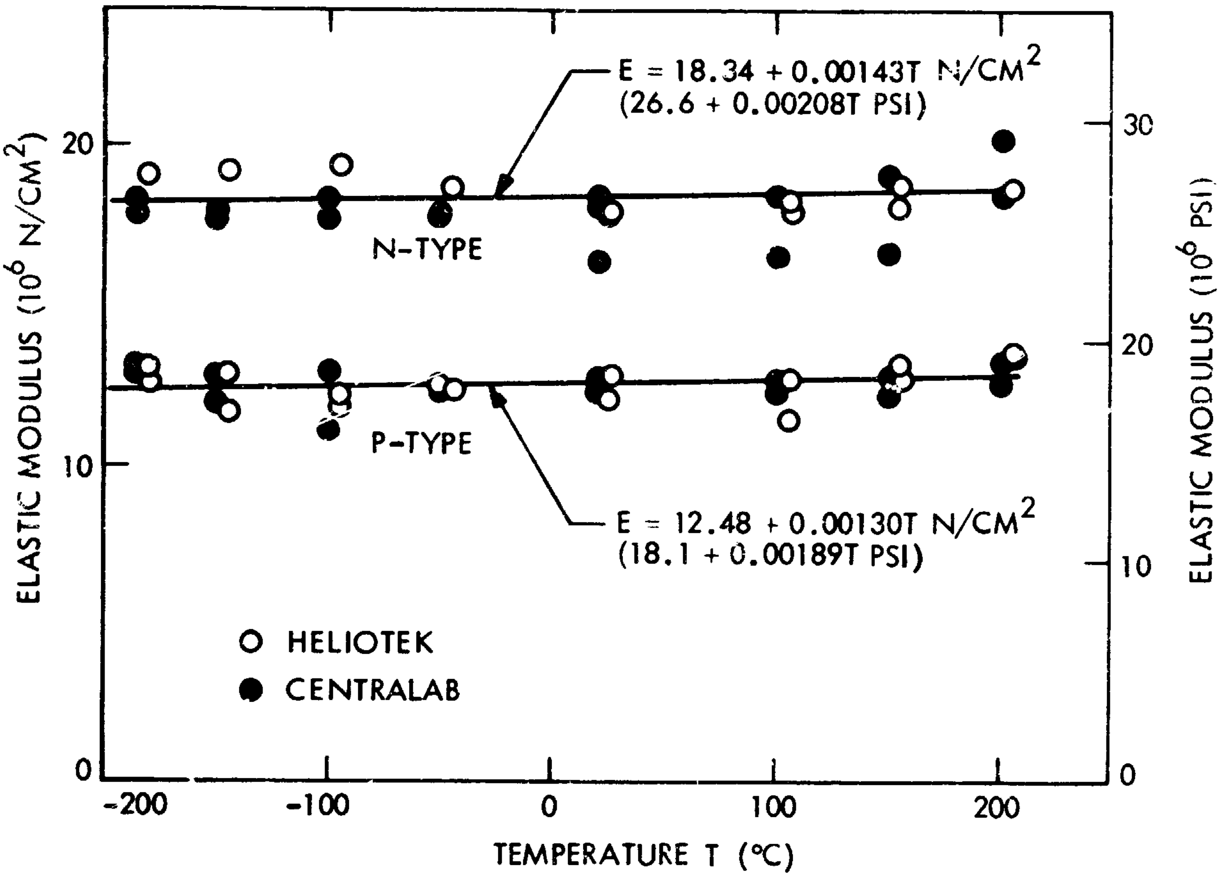


Figure 7.6-1. Single-Crystal Silicon — Elastic Modulus (Ref 7.6-2)

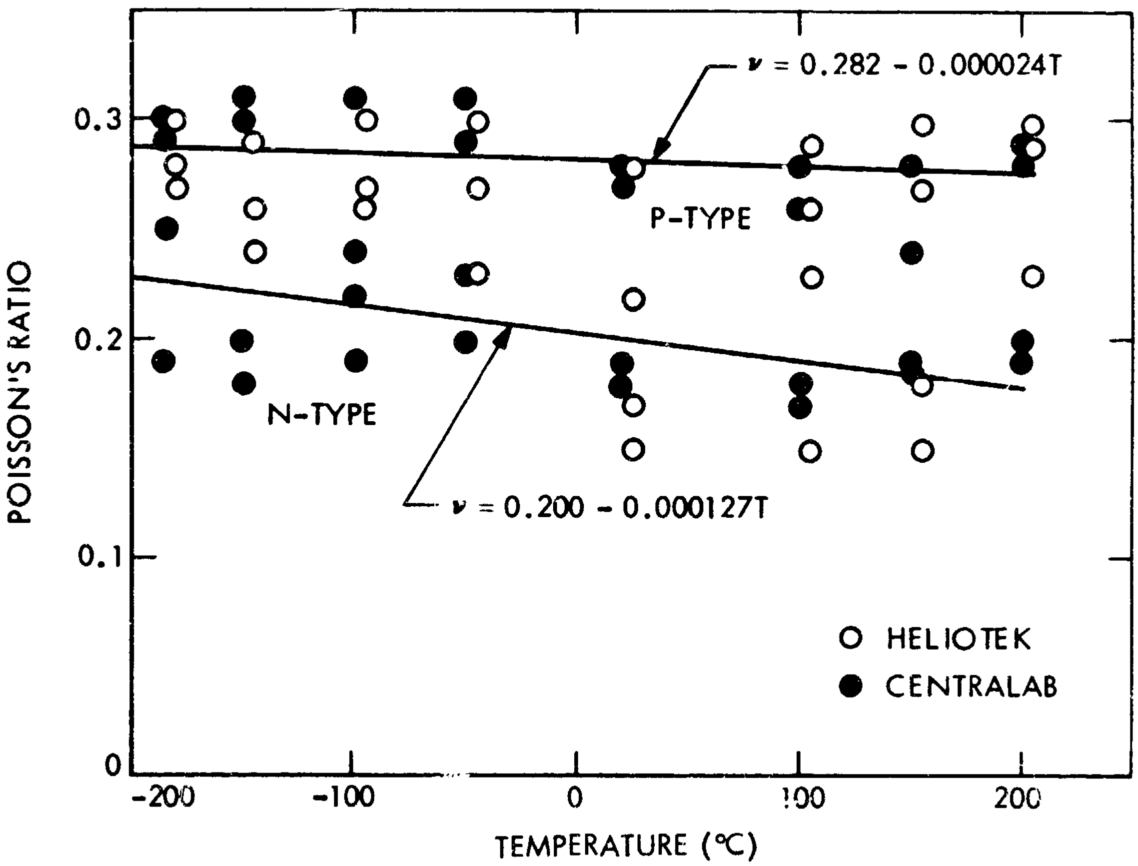


Figure 7.6-2. Single-Crystal Silicon — Poisson's Ratio (Ref 7.6-2)

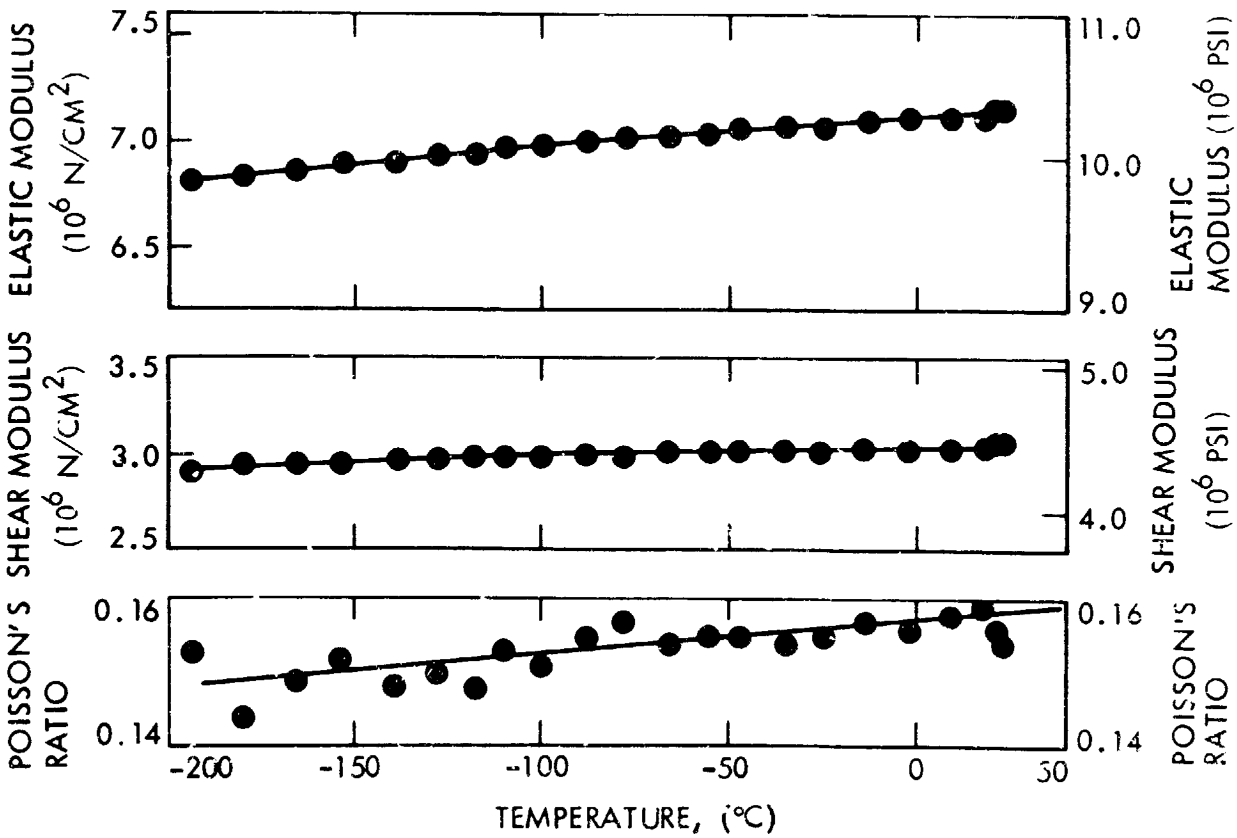


Figure 7.6-3. Fused Silica (Corning Glass 7940) – Elastic Modulus, Poisson's Ratio and Shear Modulus (Ref 7.6-2)

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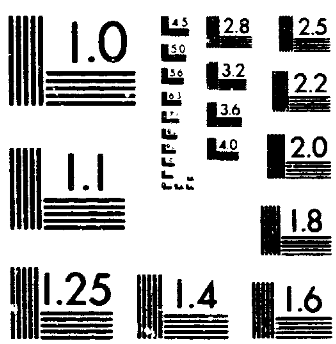

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Table 7.6-1. Ultimate Strength for Single-Crystal Silicon Tensile Specimens (Ref. 7.6-2)

Type Specimen* and Supplier	Ultimate stress, N/cm^2 (psi) x 10^{+3}			Cycles to 6895 N/cm^2 Before Failing	Fracture Description
	+25°C	-100°C	-15.0°C		
P-type, Centralab No. 4		19.0 (27.5)		33	Multiple fractures, on a single smooth plane at 40 degrees to specimen centerline
P-type, Heliotek No. 1	21.4 (31.1)			–	Multiple fractures at 45 degrees to specimen centerline
P-type, Heliotek No. 3		20.8 (39.1)		36	Multiple fractures, on two smooth planes at 40 degrees to specimen centerline
N-type, Centralab No. 3		16.5 (24.0)		36	Double fracture at 90 degrees to specimen centerline
N-type, Centralab No. 4		16.3 (33.6)		42	Single fracture, 90 degrees to specimen centerline
N-type, Heliotek No. 1		12.7 (18.5)		36	Double fracture, 90 degrees to specimen centerline
N-type, Heliotek No. 2			14.6 (21.2)	24	Single fracture, 90 degrees to specimen centerline
N-type, Heliotek No. 3			16.0 (23.2)	24	Single fracture, 90 degrees to specimen centerline
N-type, Heliotek No. 4		11.9 (17.3)		24	Multiple fractures, 90 degrees to specimen centerline

*Specimens are cylindrical rods.

Table 7.6-2. Ultimate Strength for Single-Crystal Silicon Compressive Specimens (Ref 7.6-2)

Specimen*	Maximum Stress N/cm^2 (psi) x 10^{+3}		Stress at Crack Indication	Fracture Description
	+25°C	-100°C		
P-type, No. 2 Centralab	32.2 (46.7)			Shattered. Had been loaded to -62,000 N/cm^2 (-90 ksi)
P-type, Centralab No. 3		140.4 (203.7)		Several longitudinal cracks in foot
P-type, Centralab No. 4		148.2 (215.0)	140.5 (203.8)	Did not fail
P-type Heliotek No. 2		140.5 (204.4)	90.0 (130.6)	Multiple longitudinal cracks and inclined fractures
P-type, Heliotek No. 3		143.8 (208.5)		At least two longitudinal cracks
N-type, Centralab No. 1		130.7 (189.6)	97.2 (140.9)	Shattered
N-type, Centralab No. 3		75.8 (109.9)	50.7 (73.6)	Multiple longitudinal cracks and varied fracture
N-type, Heliotek No. 1	132.0 (191.5)			Single longitudinal crack and fracture at 90 degrees to specimen centerline. Had been loaded to -48,000 N/cm^2 (-70 ksi)

*Specimens are cylindrical rods.

Notes to Table 7.6-1:

The p-type material appears to be slightly stronger in both tension and compression than the n-type. This characteristic also occurred during earlier flexural tests (Ref. 7.6-1) on actual solar cell wafer blanks. The higher strengths achieved by the p-type specimens are probably explained by their crystallographic orientation with respect to the loading direction. The p-type specimens were stressed with the weak (110) crystal direction at an angle of 40 to 50 degrees to the specimen centerline. Failure occurred preferentially along this direction in the weak (111) planes, resulting in inclined fractures. On the other hand, the n-type specimens were oriented with their longitudinal axes parallel to the stronger (111) growth direction. With this orientation the (111) planes are perpendicular to the direction of loading and fractures occur normal to the specimen centerlines. Failure for silicon almost always occurs by cleavage along the weak (111) planes (Refs. 7.6-4 and 7.6-5).

In summary, the ultimate strength ranges at 25°C from 100 to 600 MN/m^2 for p-type silicon with a phosphorous layer on one side. The range is partly caused by prestressing of silicon by the phosphorous diffusion which results in an average strength of 210 MN/m^2 when loaded in the direction of the prestressing as compared to 460 MN/m^2 when loaded against the prestressing and partly by scatter in strength, 100 to 280 MN/m^2 in the first case and 290 to 600 MN/m^2 in the second case.

Wide variations in ultimate strength are caused by surface preparation. Strongly etched surfaces result in average strength of 210 MN/m^2 with the diffused layer in tension as compared to mechanically worked and lightly etched surfaces of 150 MN/m^2. With the diffused layer in compression, the corresponding values are 180 and 100 MN/m^2, respectively. The rougher surfaces on the undiffused side obtained by sandblasting and light etching contain many microfissures and cracks which behave as stress risers when this surface is in tension, resulting in the lower strength and greater scatter of ultimate strength.

For lithium doped cells, ultimate strength as low as 63 MN/m^2 has been recorded.

The elastic modulus at 25°C ranges from 37 to 84 GN/m^2 for n-p cells. There is no correlation of low elastic modulus with low ultimate strength.

7.7 ELASTIC MODULUS, POISSON'S RATIO AND ULTIMATE STRENGTH OF OTHER NON-METALS

The following data is included in this section:

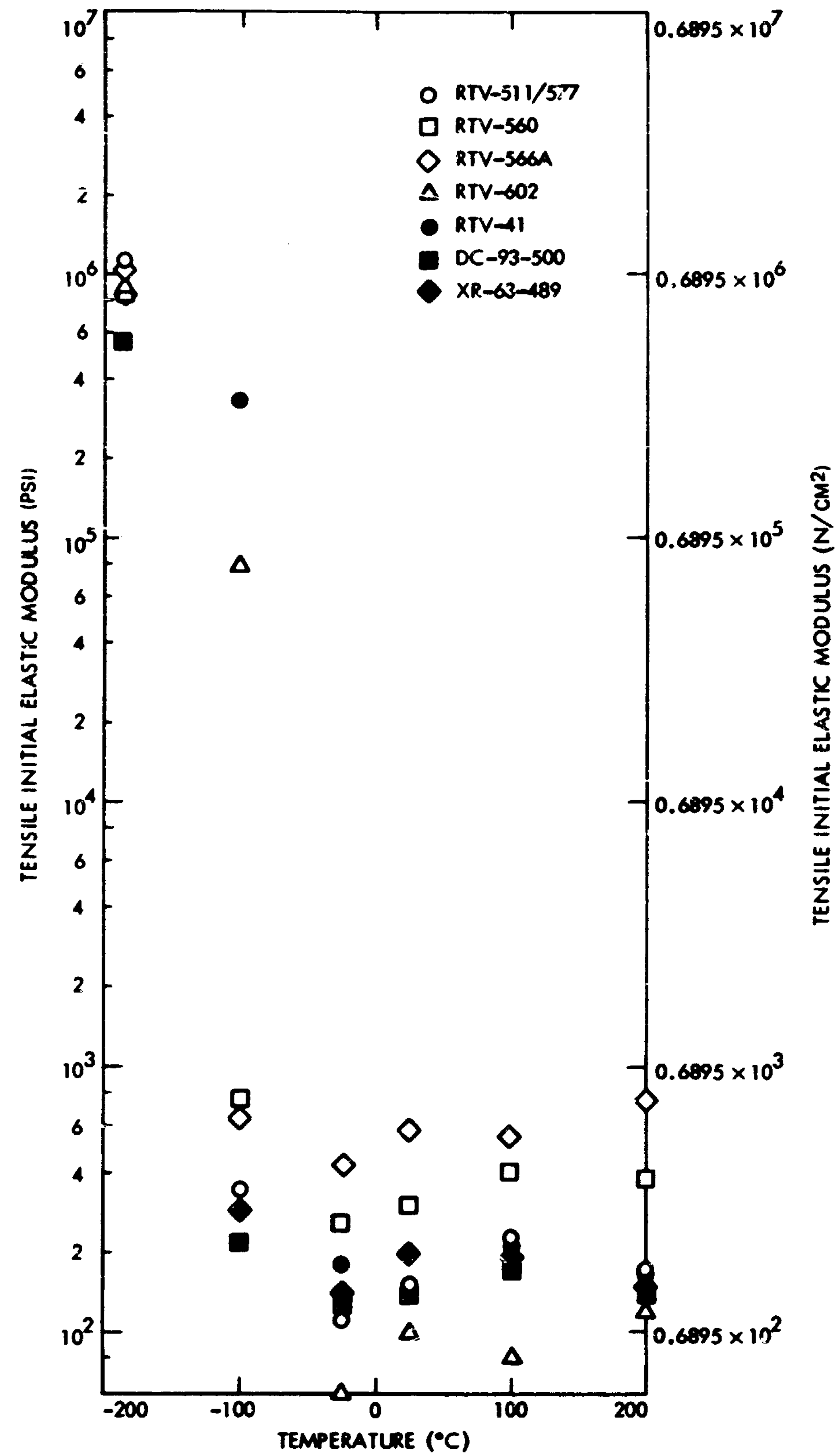


Figure 7.7-1. Silicone Rubbers -- Initial Elastic Modulus in Tension (Ref 7.7-2)

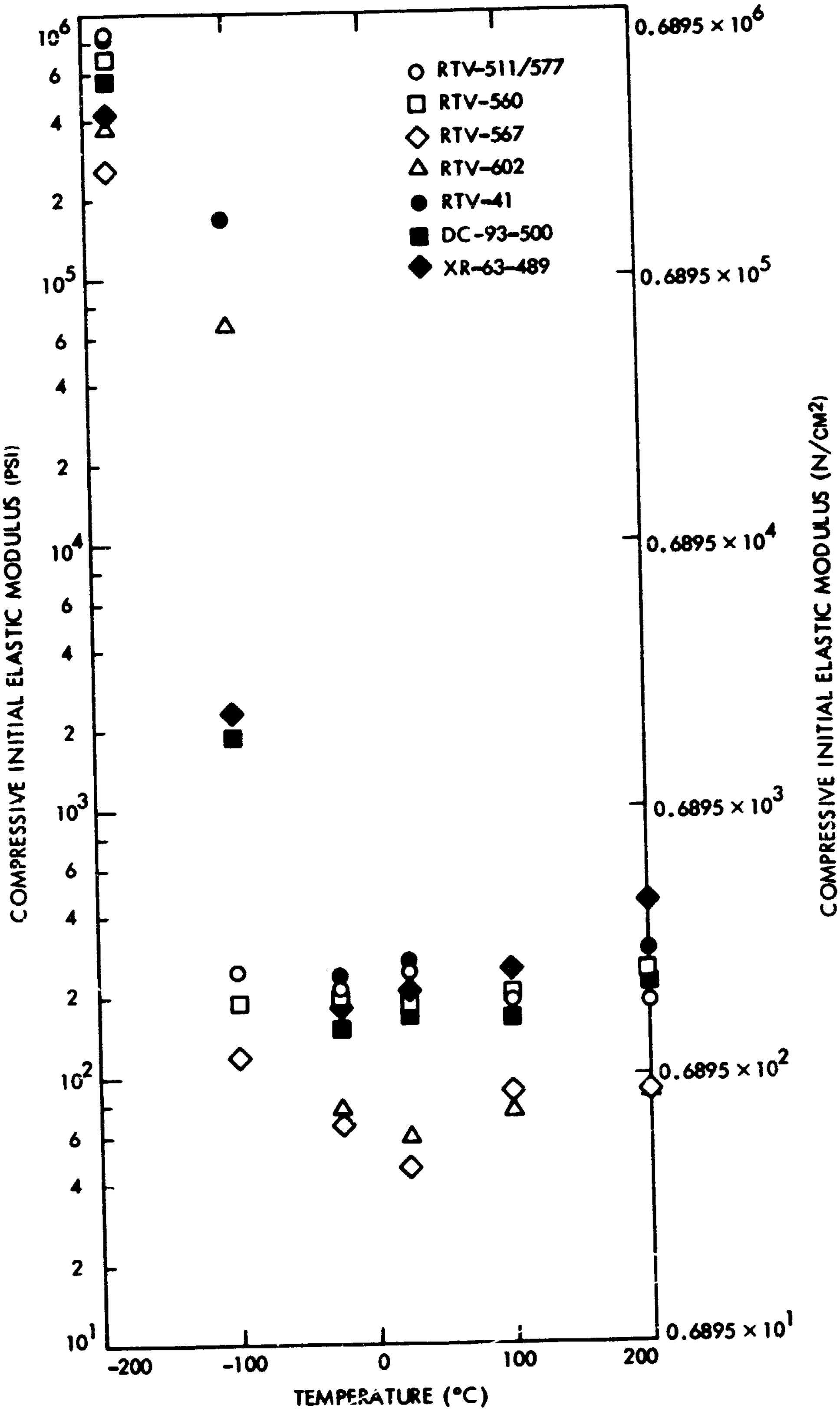


Figure 7.7-2. Silicone Rubbers — Initial Elastic Modulus in Compression (Ref 7.7-2)

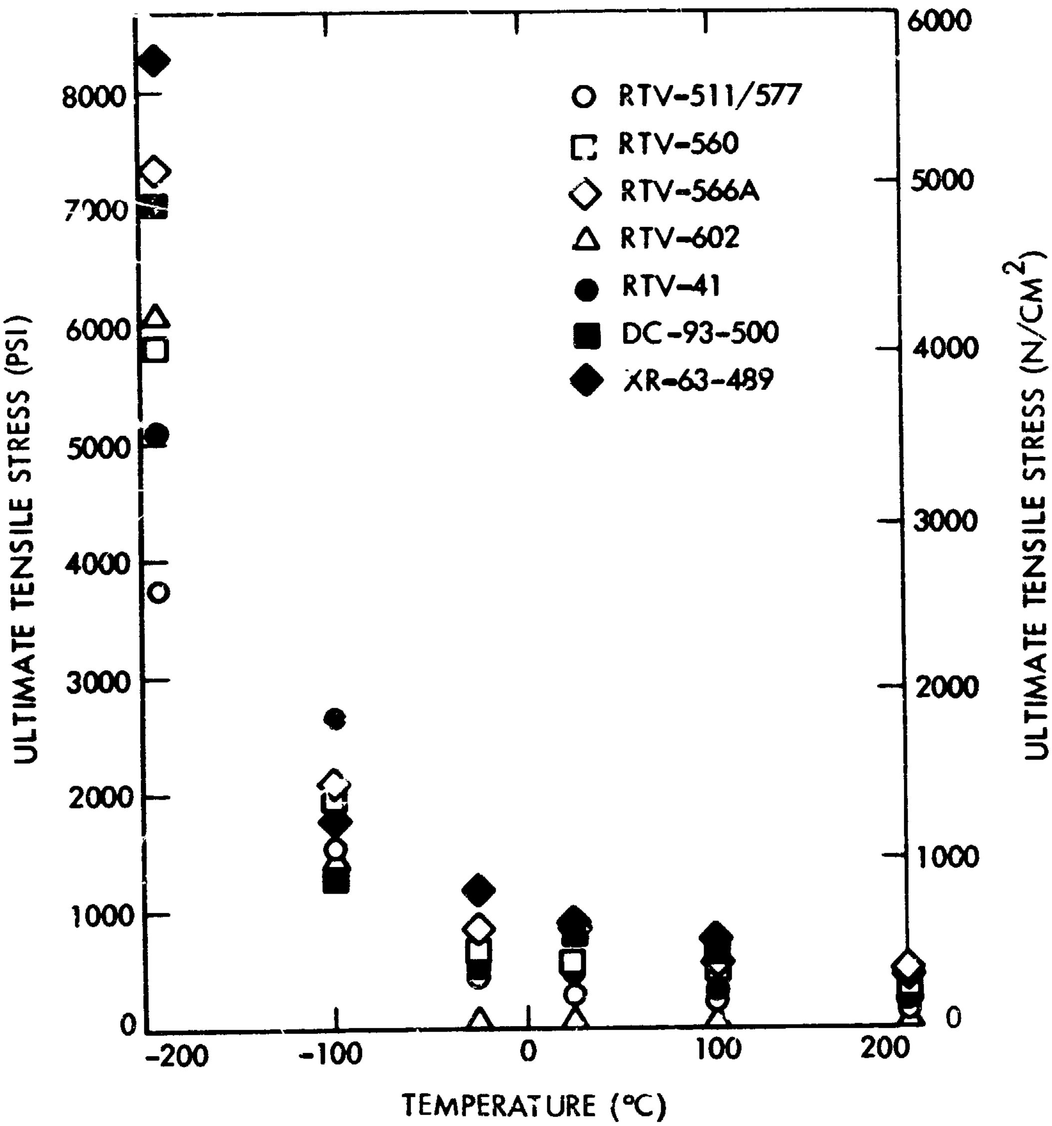


Figure 7.7-3. Silicone Rubbers — Ultimate Tensile Strength (Ref 7.7-2)

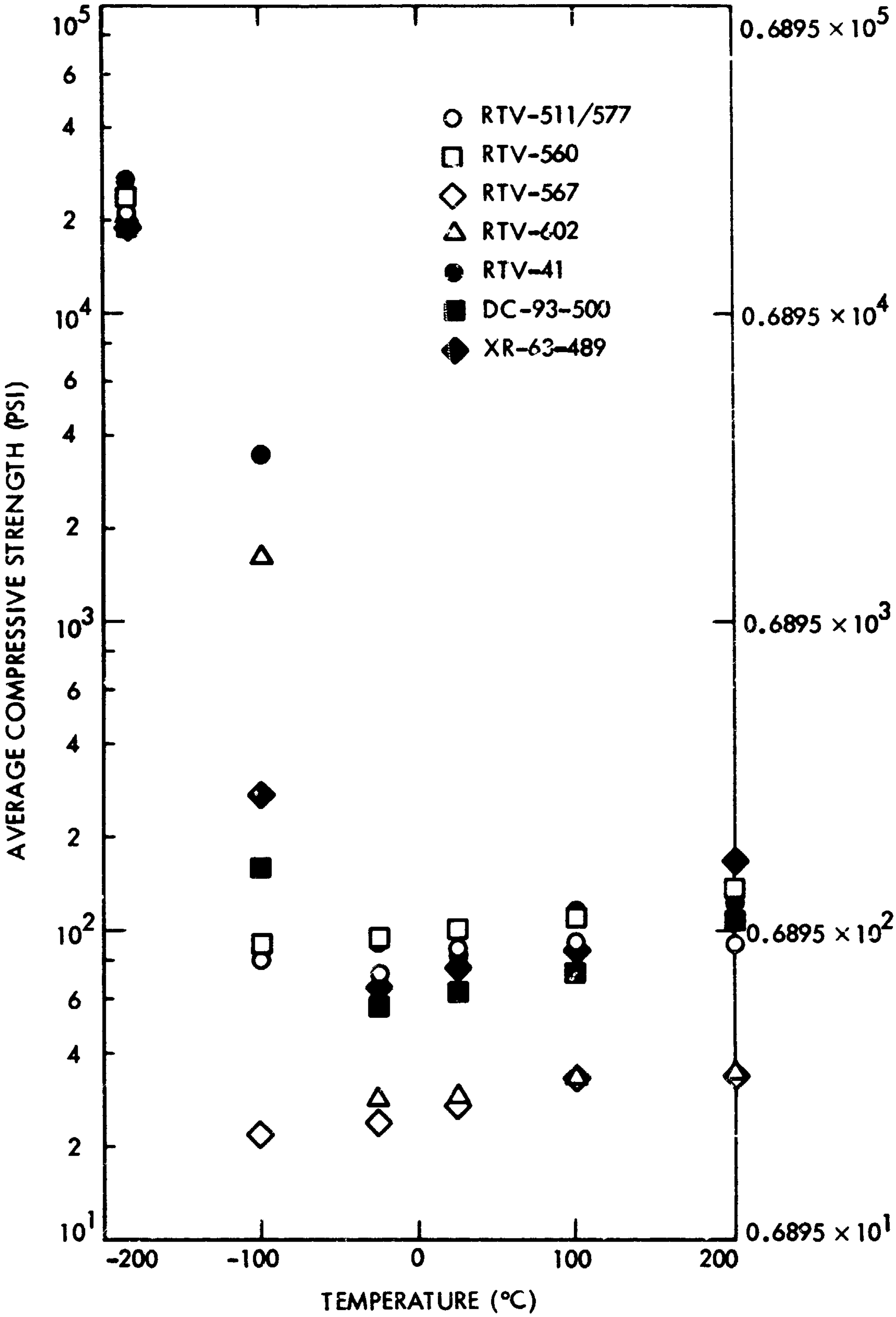


Figure 7.7-4. Silicone Rubbers — Compressive Strength (Ref 7.7-2)

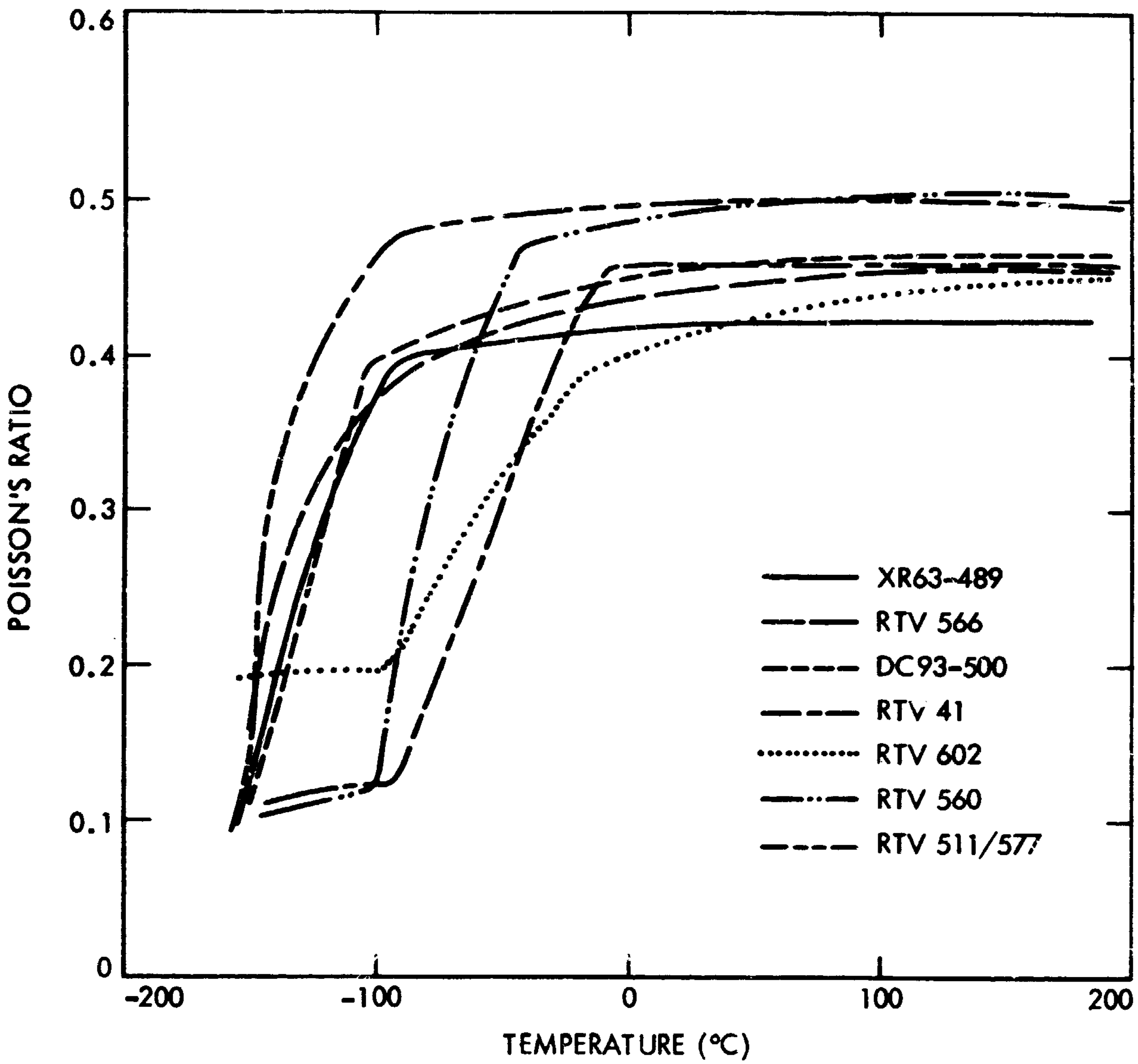


Figure 7.7-5. Silicone Rubbers — Poisson's Ratio (Ref 7.7-2)

Table 7.7-1. Properties of RTV 118 (Ref 7.7-3)

Temperature °C	α 10^{-6}/°C	E MN/m^2	G MN/m^2	Yield Strength MN/m^2	Poisson's Ratio
-200	134	2070	690	83	0.45
-170	180	1200	345	69	0.45
-100	290	210	69	14	0.45
+20	440	0.21	0.07	1.4	0.45

Table 7.7-2. Strength of Kapton (Ref. 7.7-3)

T (°C)	E (GN/m^2)	3 Percent Yield Strength (MN/m^2)	Ultimate Strength (MN/m^2)
-196	3.5	--	240
25	3.0	69	170
200	1.8	41	120

Kapton has a 10,000-cycle folding endurance when tested per ASTM D-2176-63T. The Elmendorf propagating tear strength per ASTM D-1922-61T is 3.2 N/mm and the Graves initial tear strength per ASTM D-1004-61 is 200 N/mm.

7.8 ELONGATION AND REDUCTION IN AREA

The available data for the materials discussed in previous sections of this chapter is shown in Table 7.8-1.

Table 7.8-1. Elongation and Reduction in Area of Several Metals

Material	Elongation (%)	Reduction in Area (%)	Temperature (°C)	Reference
Invar, annealed	41	72	25	7.5-7
Invar, 15 percent cold-worked	14	64	25	7.5-7
Kovar		69	21	7.5-5 and 7.5-6
Kovar		73	73	7.5-5 and 7.5-6
Silver (fine), annealed	48		20	7.5-13
Silver, 50 percent cold worked	2.4		20	7.5-13
Molybdenum sheet		0	-75	7.5-10
Molybdenum sheet		5	-40	7.5-10
Molybdenum sheet		35	0	7.5-10
Molybdenum sheet		58	40	7.5-10
Molybdenum sheet		60	70	7.5-10
Molybdenum bar		15	-75	7.5-10
Molybdenum bar		45	-40	7.5-10
Molybdenum bar		70	0	7.5-10
Molybdenu bar		75	40	7.5-10
Molybdenum bar		80	70	7.5-10

7.9 ELECTRICAL PROPERTIES OF CONDUCTORS

This section contains a tabular presentation of the electrical resistivity of several metals (Table 7. 9-1).

Table 7. 9-1. Electrical Resistivity of Several Metals

Material	Resistance Relative To Copper	Resistivity at 20°C (micro-ohm · cm)
Aluminum	1.64	2.65 - 2.83
Brass	3.9	6.7
Beryllium-Copper	3.1	5.32
Constantan	28.45	49.1
Copper, annealed	1.00	1.7241
Copper, hard-drawn	1.03	1.7758
Gold	1.416	2.42
Indium	9.0	15.5
Invar	47.6	82
Iron, pure	5.6	9.7
Kovar	28.4	49
Lead	12.78	22
Molybdenum	3.3	5.7
Nickel	5.05	6.84
Palladium	6.2	10.7
Silver	0.95	1.59 - 1.6
Tin	6.7	11.6
Titanium	47.8	42
Tungsten	3.25	5.6

7.10 ELECTRICAL PROPERTIES OF DIELECTRICS

The following data is included in this section:

- Figure 7.10-1. Short Time Dielectric Strength Versus Thickness of FEP-Teflon
- Figure 7.10-2. Insulation Life Versus Continuously Applied Voltage Stress of FEP-Teflon
- Figure 7.10-3. Volume Resistivity of Kapton Versus Temperature
- Figure 7.10-4. AC Dielectric Strength of Kapton Versus Temperature
- Figure 7.10-5. Dielectric Constant of Kapton Versus Temperature
- Table 7.10-1. Surface and Volume Resistivity of Teflon at Various Temperatures
- Table 7.10-2. Typical Electrical Properties of Kapton Polyimide Film
- Table 7.10-3. Electrical Properties of 25 μm thick Kapton Versus Relative Humidity
- Table 7.10-4. AC Dielectric Life of Kapton
- Table 7.10-5. Electrical Properties of Corning Fused Silica Code 7940
- Table 7.10-6. Electrical Properties of 0210 Microsheet Glass at Room Temperature

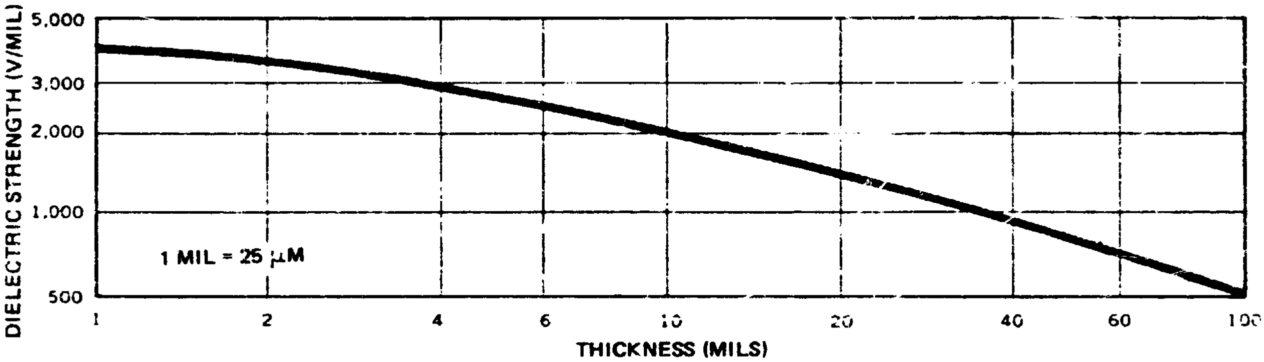


Figure 7.10-1. Short Time Dielectric Strength Versus Thickness of FEP Teflon (Ref. 7.10-1)

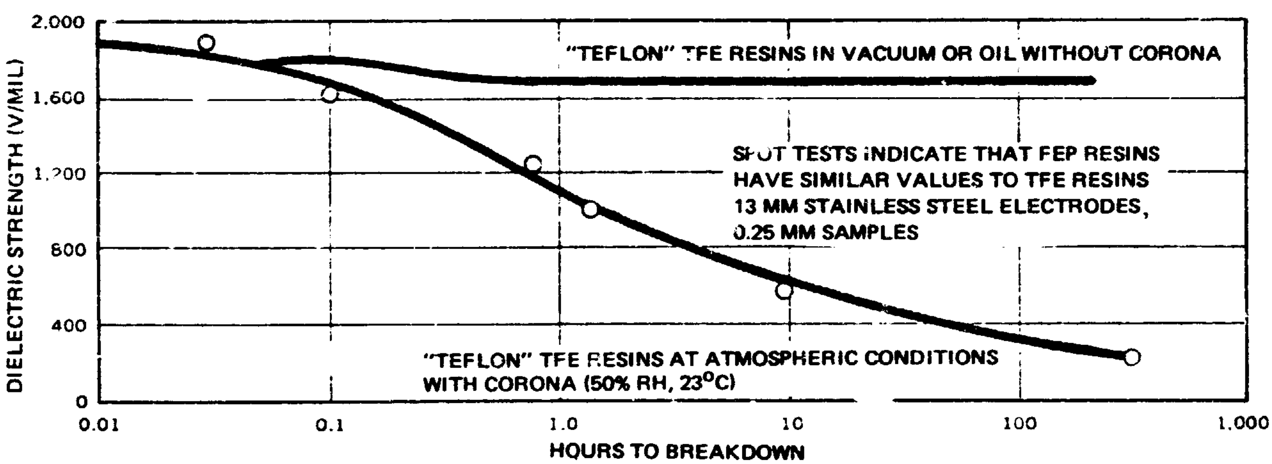


Figure 7.10-2. Insulation Life Versus Continuously Applied Voltage Stress of FEP Teflon (Ref. 7.10-1)

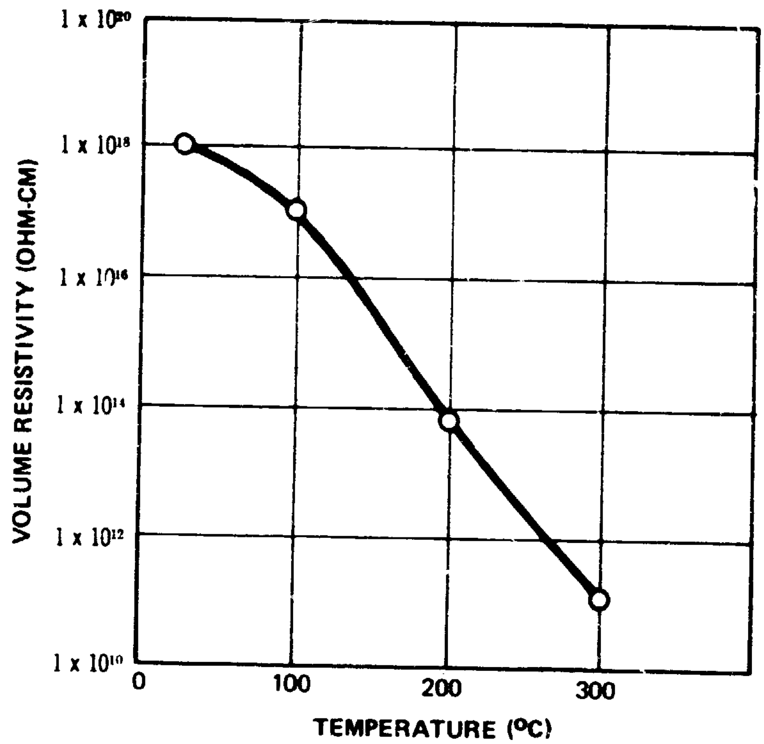


Figure 7. 10-3. Volume Resistivity of Kapton Versus Temperature (Ref. 7. 10-2)

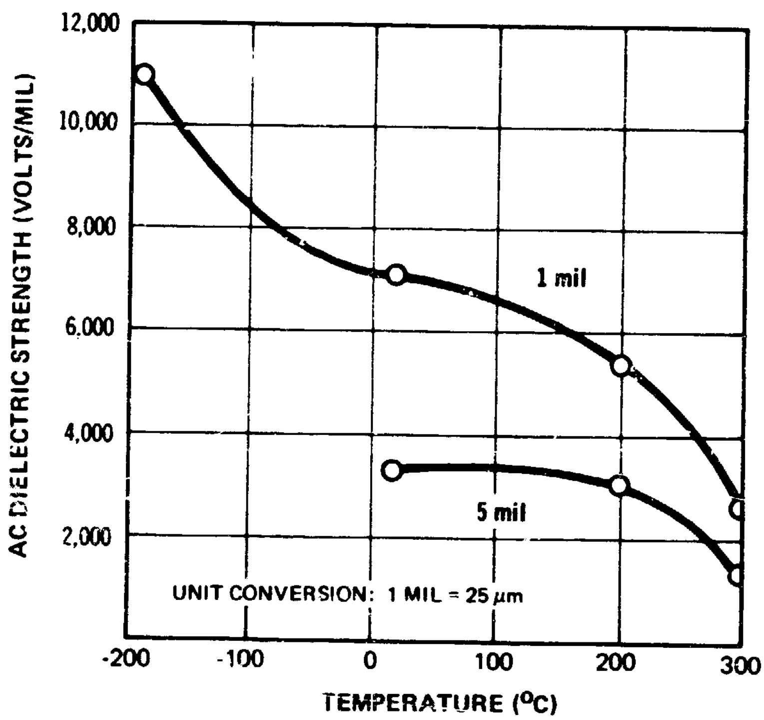


Figure 7. 10-4. AC Dielectric Strength of Kapton Versus Temperature (60 Hz, 6. 4 mm diameter electrodes; Ref. 7. 10-2)

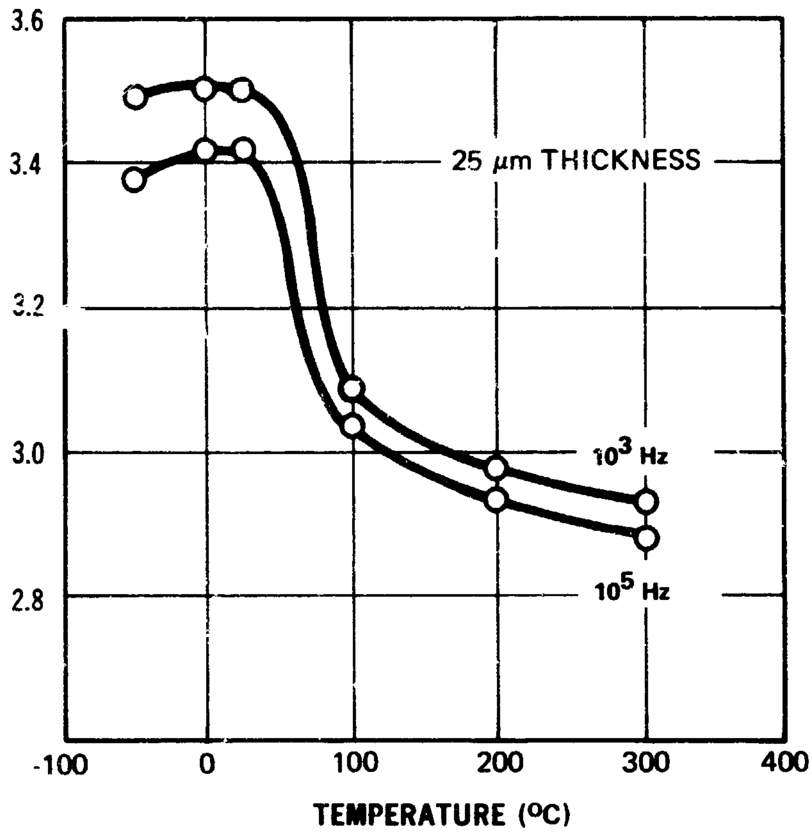


Figure 7.10-5. Dielectric Constant of Kapton Versus Temperature (Ref. 7.10-2)

Table 7.10-1. Surface and Volume Resistivity of Teflon at Various Temperatures (Ref. 7.10-1)

Resins	Volume Resistivity (ohm•cm)	Surface Resistivity (ohm/sq)	Measured Temperature Range
TFE	$>10^{18}$	$>10^{16}$	-40°F (-40°C) to 440°F (227°C)
FEP	$>10^{18}$	$>10^{16}$	-40°F (-40°C) to 440°F (227°C)

Table 7.10-2. Typical Electrical Properties of Kapton Polyimide Film (Ref. 7.10-2)

PROPERTY	TYPICAL VALUE	TEST CONDITION	TEST METHOD
Dielectric Strength			
1 mil	7,000 v/mil	60 cycles ¼" electrodes	ASTM D 149-61
2 mil	5,400 v/mil		
3 mil	4,600 v/mil		
5 mil	3,600 v/mil		
Dielectric Constant			
1 mil	3.5	1 kilocycle	ASTM D-150-59T
2 mil	3.6		
3 mil	3.7		
5 mil	3.7		
Dissipation Factor			
1 mil	.0025	1 kilocycle	ASTM D-150-59T
2 mil	.0019		
3 mil	.0017		
5 mil	.0017		
Volume Resistivity			
1 mil	1×10^{18} ohm-cm	125 volts	ASTM D-257-61
2 mil	8×10^{17} ohm-cm		
3 mil	5×10^{17} ohm-cm		
5 mil	1×10^{17} ohm-cm		
Corona Threshold Voltage			
1 mil	465 volts	60 cycles ¼" electrodes	ASTM 1868-61T
2 mil	550 volts		
3 mil	630 volts		
5 mil	800 volts		
5 mil H/2 mil FEP/ 5 mil H/½ mil varnish	1,600 volts		

*Du Pont trademark

Table 7.10-3. Electrical Properties of 25 μm thick Kapton Versus Relative Humidity (Ref. 7.10-2)

% RELATIVE HUMIDITY	AC DIELECTRIC STRENGTH	DIELECTRIC CONSTANT	DISSIPATION FACTOR
0	7,300 v/mil	3.0	.0018
30	7,300 v/mil	3.3	.0021
50	7,000 v/mil	3.5	.0025
80	6,500 v/mil	3.7	.0037
100	6,200 v/mil	3.9	.0047

Table 7.10-4. AC Dielectric Life of Kapton (25°C, 6.4 mm Diameter Electrodes; Ref. 7.10-2)

25 μm Type H-Film		125 μm Type H Plus 50 μm FEP-Teflon	
Corona Threshold Voltage	465 Volts	Corona Threshold Voltage	1600 Volts
Voltage (volt)	Life (sec)	Voltage (volt)	Life (hour)
1,000	30,000		
2,500	2,990	6,000	525
3,000	1,260	9,000	25
4,000	265		
4,500	144		
5,000	72		
5,500	33		
6,000	18		
6,500	9		

Table 7.10-5. Electrical Properties of Corning Fused Silica Code 7940 (Ref. 7.10-3)

Parameter	Test Temperature (^{o}C)	Value
Dielectric Constant:	25	3.85
10^5 and 10^{10} Hz	250	3.85
	500	3.85
Loss Tangent:	25 and 295	<0.00002
10^5 Hz	385	0.0001
	490	0.001
Volume Resistivity:	200	13.2
Log_{10} R (ohm • cm)	400	9.8

Table 7.10-6. Electrical Properties of 0211 Microsheet Glass at Room Temperature (Ref. 7.10-4)

Frequency (Hz)	(Power Factor) Loss Tangent	Dielectric Constant
60	0.01	7.0
10^6	0.0029	6.9

7.11 THERMAL EXPANSION PROPERTIES

Data for the following materials is shown in the figures and tables as indicated:

• Aluminum	Figure 7.11-1
• Copper	Figure 7.11-2
• FEP-Teflon	Figure 7.11-3
• Invar	Figure 7.11-4
• Kapton	Figure 7.11-4 and Table 7.11-1
• Kovar	Figures 7.11-4 and 7.11-5
• Molybdenum	Figures 7.11-4 and 7.11-5
• Silica, Fused	Figures 7.11-5 and 7.11-6
• Silicon	Figures 7.11-5 and 7.11-6
• Silicone Rubbers	Figures 7.11-7 and 7.11-8
• Silver	Figures 7.11-4, 7.11-5, and Table 7.11-2
• Solder	Figure 7.11-5

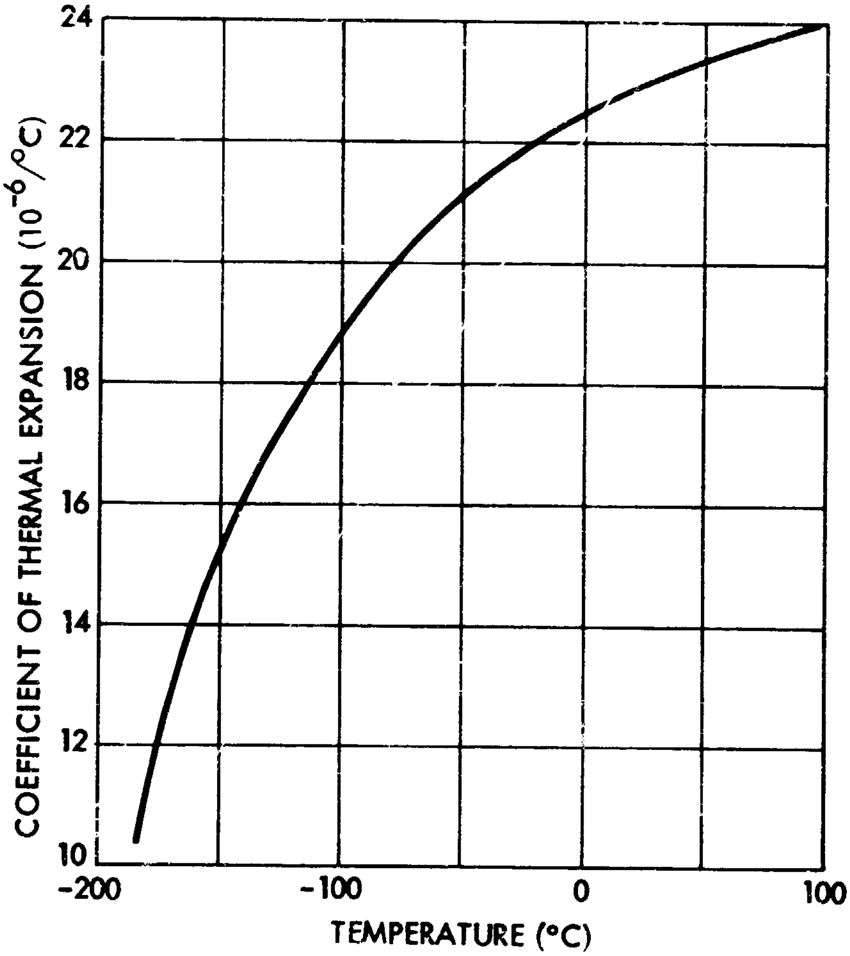


Figure 7.11-1. Average Coefficient of Thermal Expansion of Aluminum (Ref. 7.11-17)

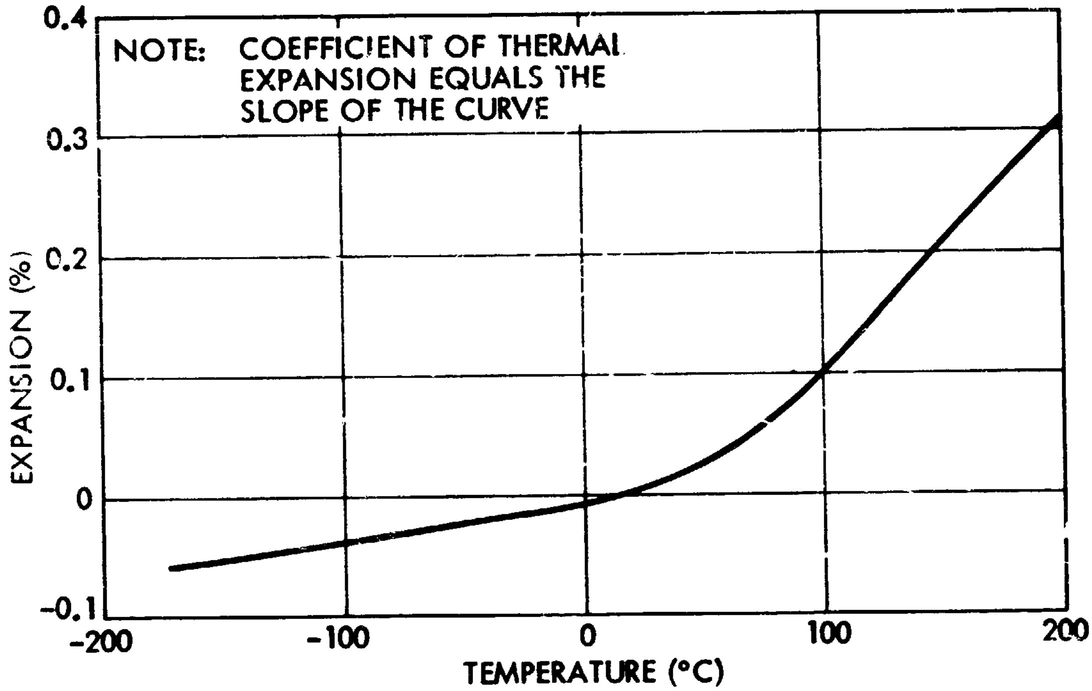


Figure 7.11-2. Linear Thermal Expansion of Copper (Ref. 7.11-17)

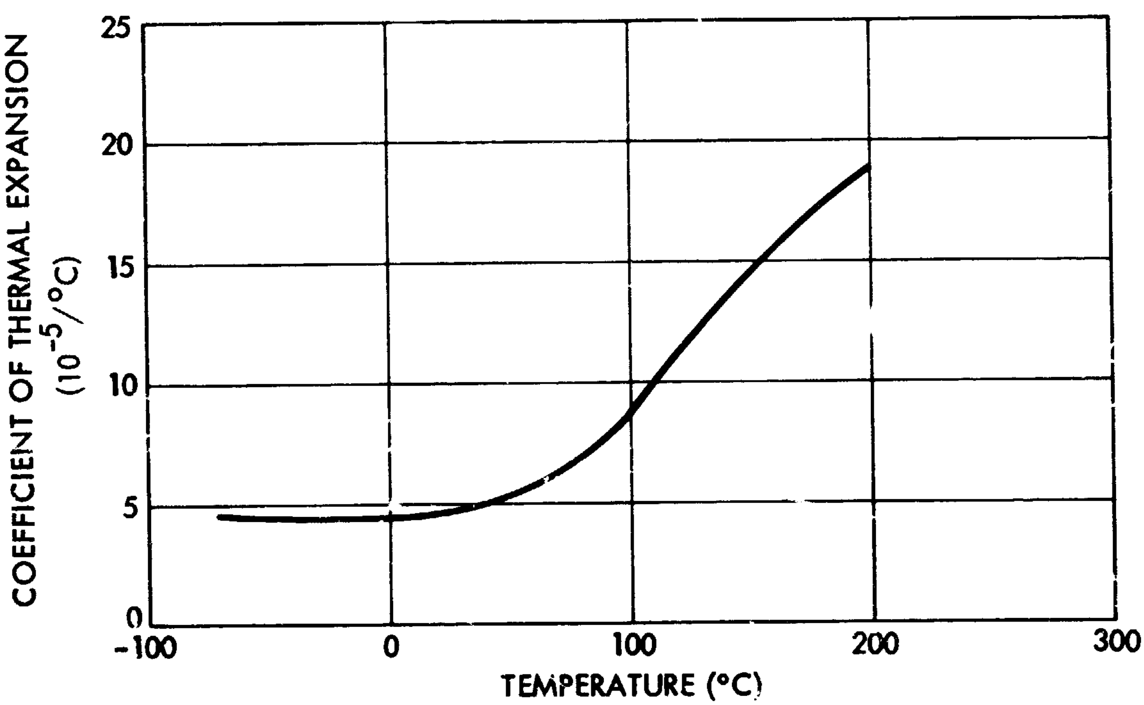


Figure 7.11-3. Average Coefficient of Thermal Expansion of FEP-Teflon (Ref. 7.11-17)

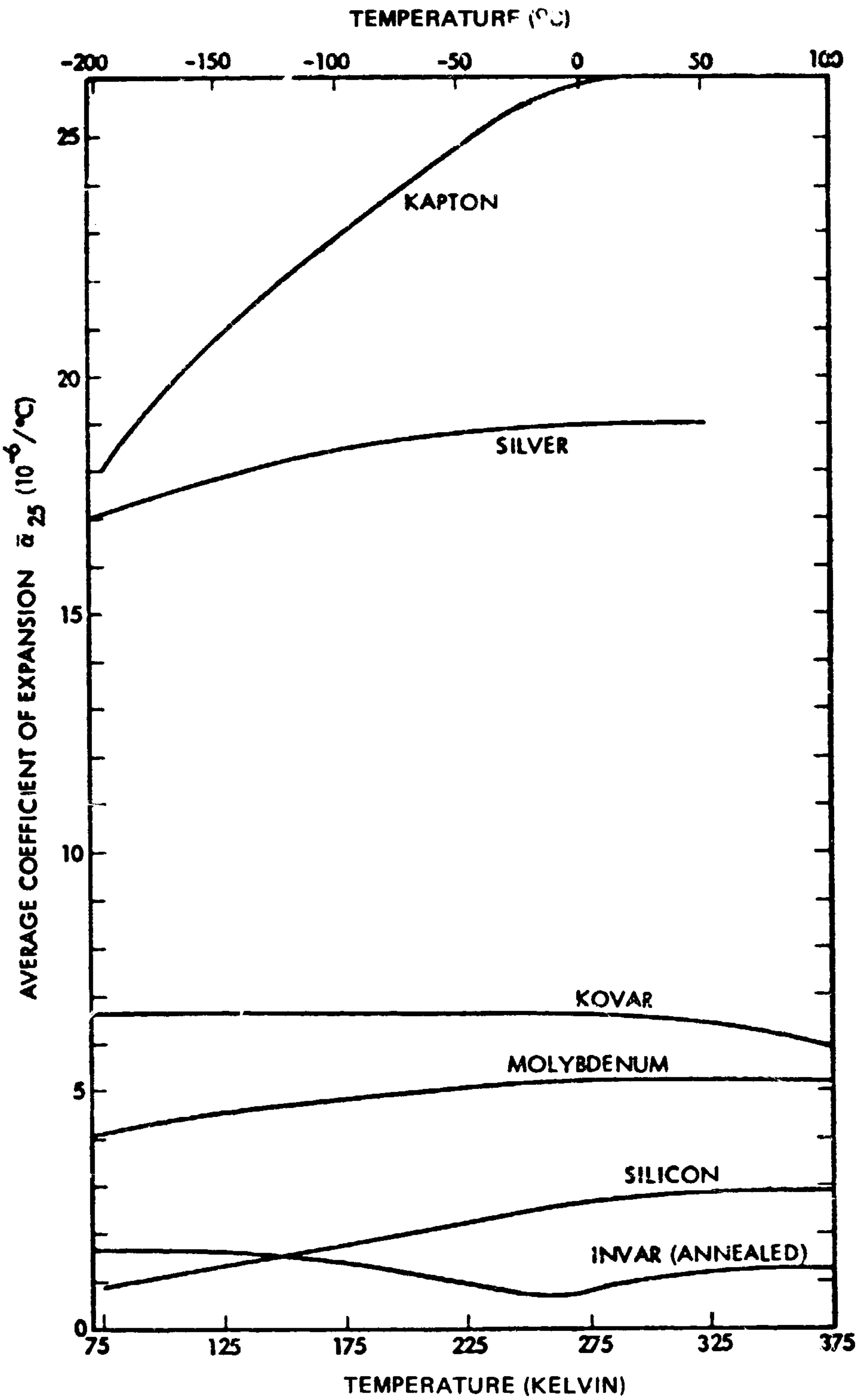


Figure 7. 11-4. Coefficient of Thermal Expansion Versus Temperature for Several Materials

(Refs: Kapton - 7. 11-3 Molybdenum - 7. 11-6
Silver - 7. 11-11 and -18 Silicon - 7. 11-2
Kovar - 7. 11-4 and -5 Invar - 7. 11-7, -8, and -9)

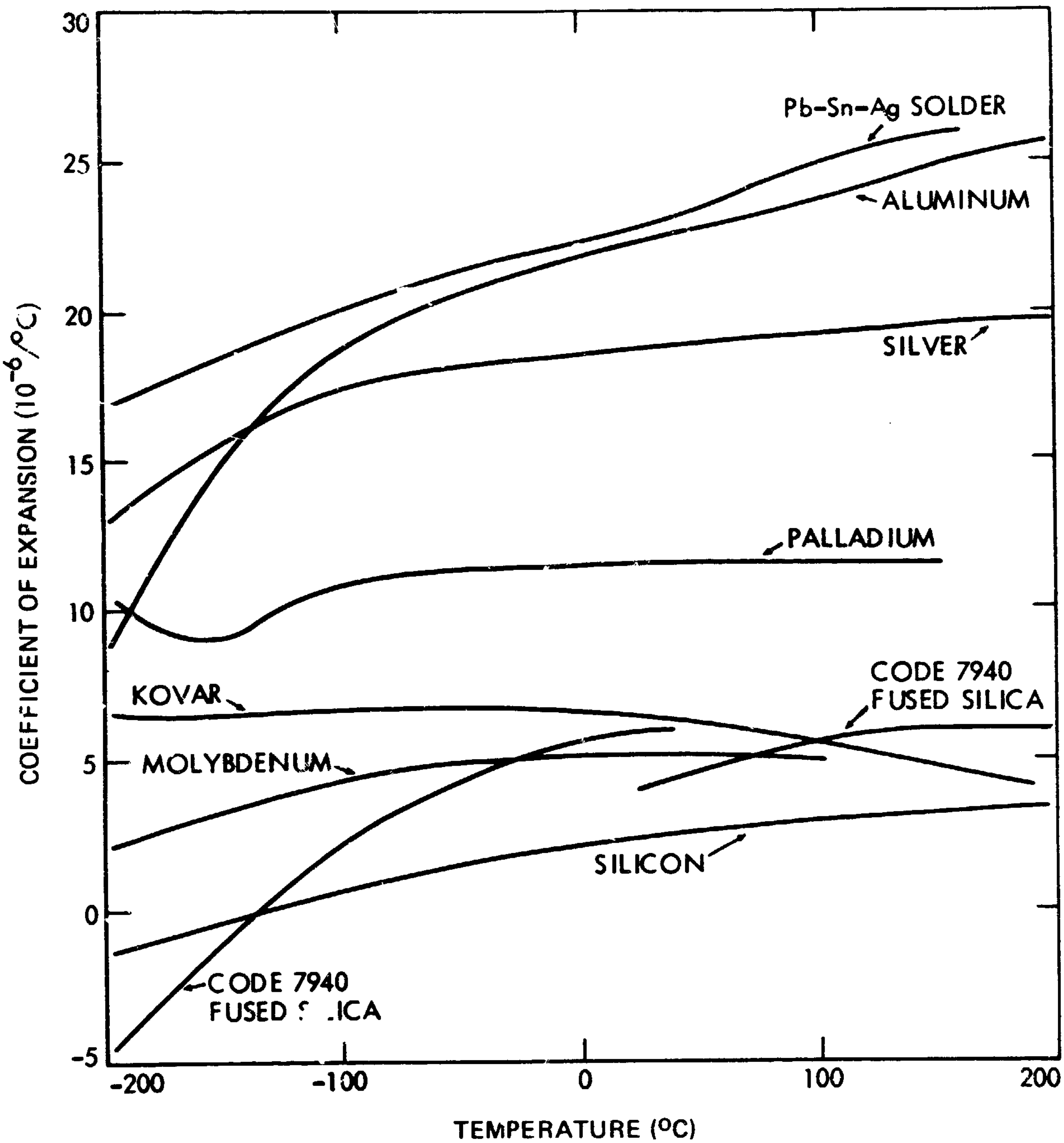


Figure 7.11-5. Coefficient of Thermal Expansion Versus Temperature for Silicon, Fused Silica and Various Metals and Alloys (Ref. 7.11-1)

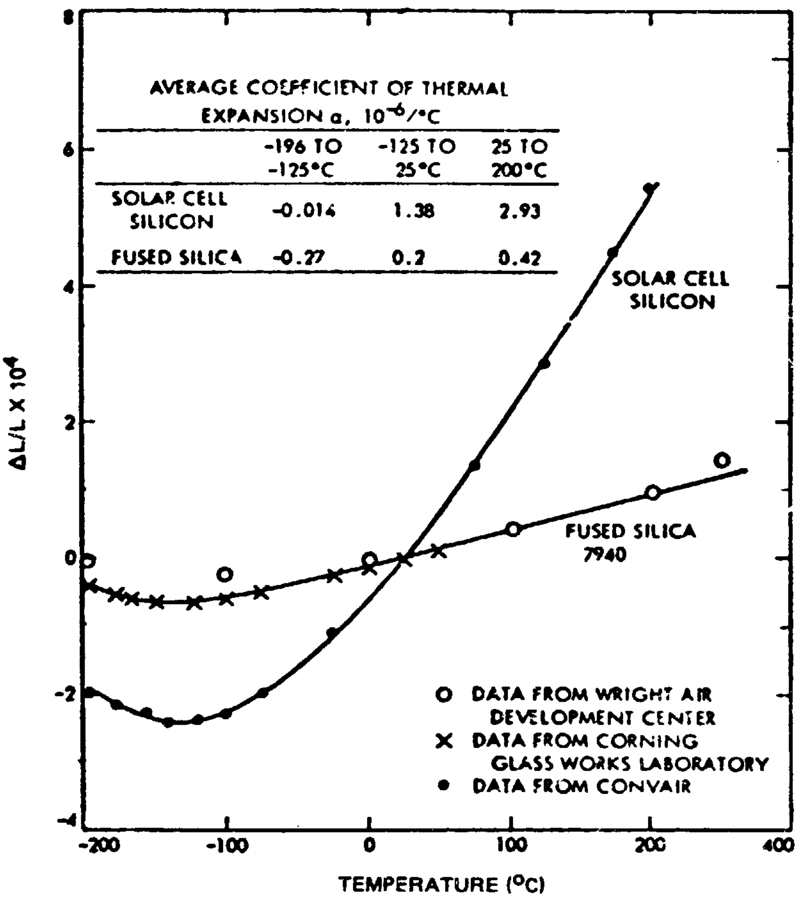


Figure 7.11-6. Change in Relative Length with Temperature for Solar Cell Silicon and for Fused Silica Code 7940 (Ref. 7.11-2)

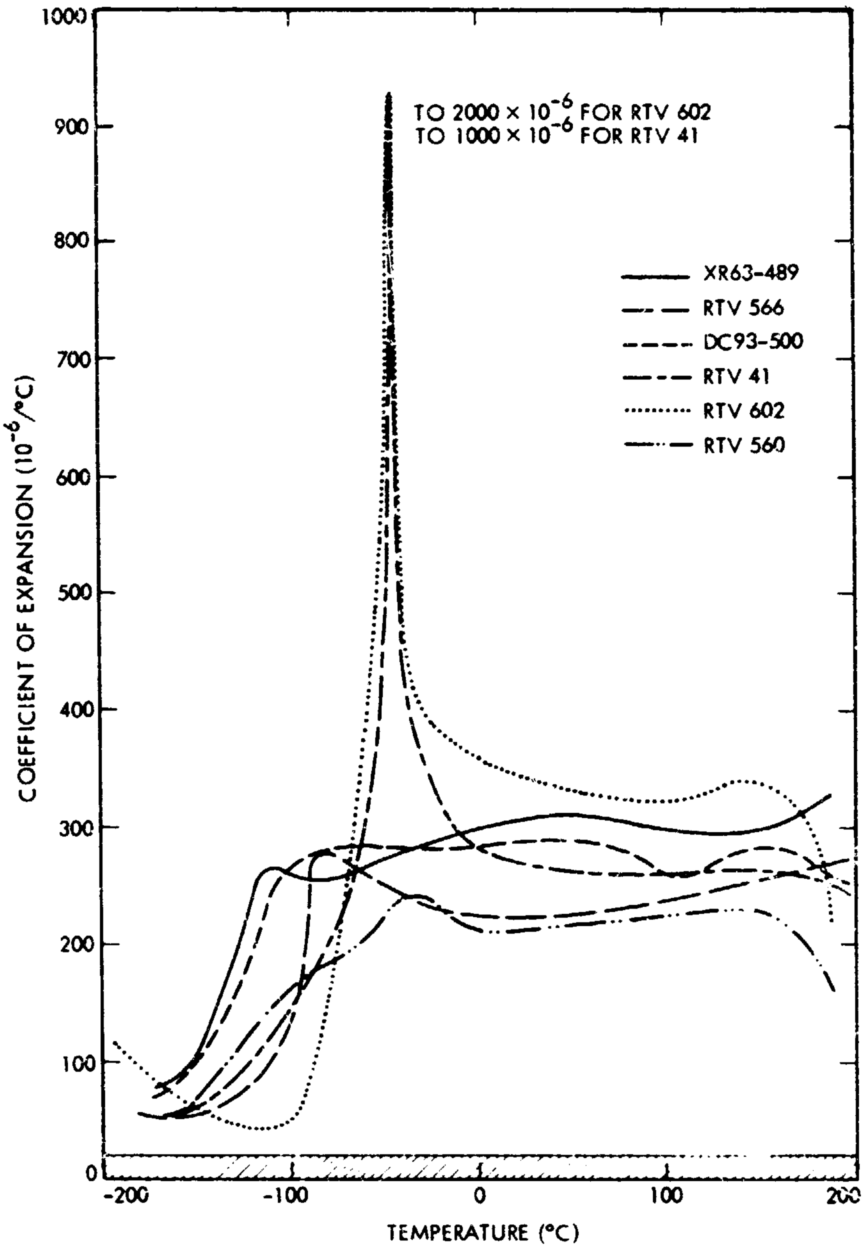


Figure 7. 11-7. Instantaneous Coefficient of Thermal Expansion for Six RTV-Type Silicone Rubber Adhesives (Ref. 7. 11-1)

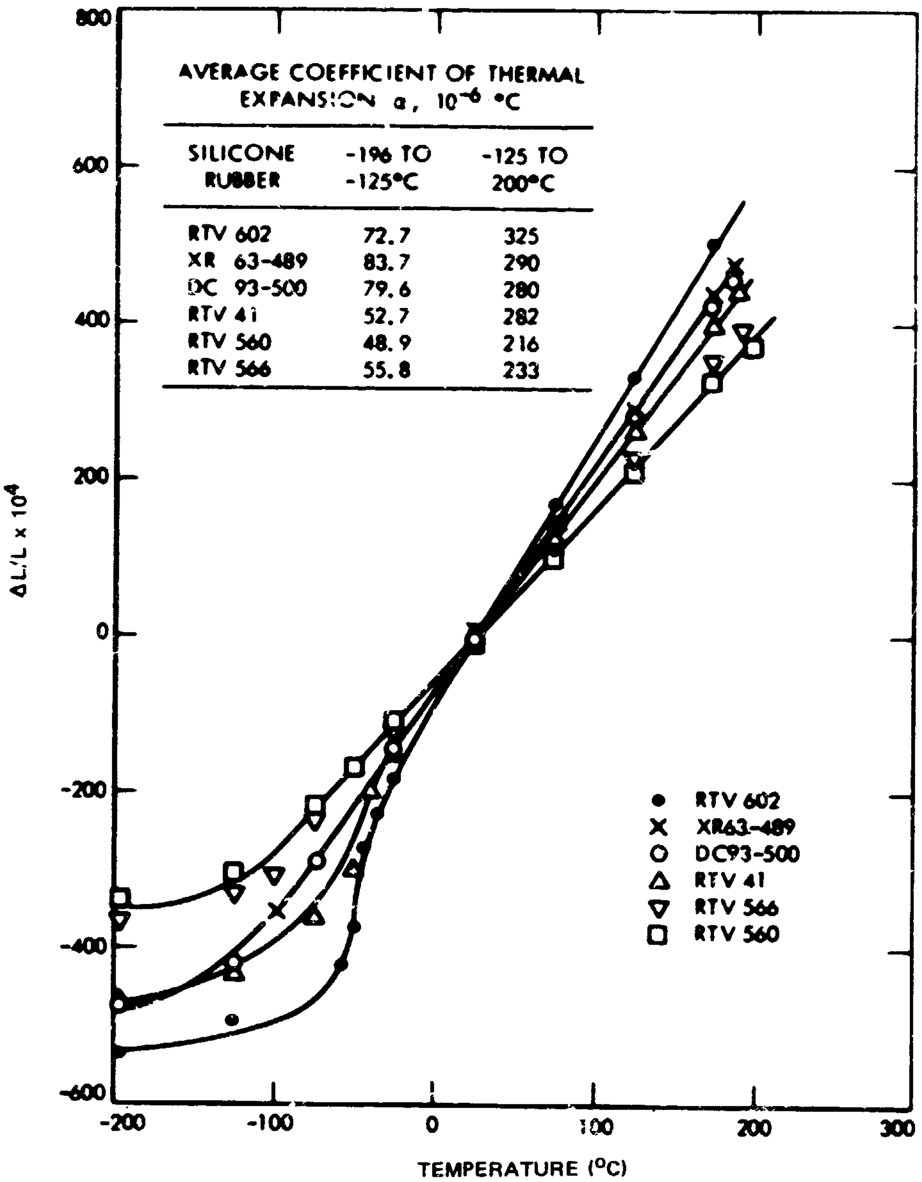


Figure 7.11-8. Thermal Expansion of Silicone Rubber Adhesives (Ref. 7.11-2)

Table 7.11-1. Average Coefficients of Expansion for Kapton

T (°C)	$\bar{\alpha}$ (10^{-6}/°C) Ref. 7.11-9	Ref. 7.11-3
-200	—	18
-150	—	21
-100	—	23
0	—	26
100	18	—
200	25	—

Table 7.11-2. Instantaneous Coefficients of Expansion for Pure Silver

T (K)	T (°C)	α (10^{-6}/K) Ref. 7.11-11	Ref. 7.11-18
310	37	19.08	—
300	27	—	19.0
298	25	18.96	—
270	-3	18.64	—
250	-23	—	18.9
210	-63	17.85	—
200	-73	—	18.2
150	-123	16.66	16.6
110	-163	15.01	—
100	-173	—	14.4
90	-183	14.06	—
70	-203	—	11.7

7.12 SPECIFIC HEAT AND HEAT CONDUCTANCE

The following data is included in this section:

- Figure 7.12-1. Specific Heat Capacity for Various Materials
- Figure 7.12-2. Specific Heat Capacity of Fused Silica
- Figure 7.12-3. Thermal Conductivity of Fused Silica

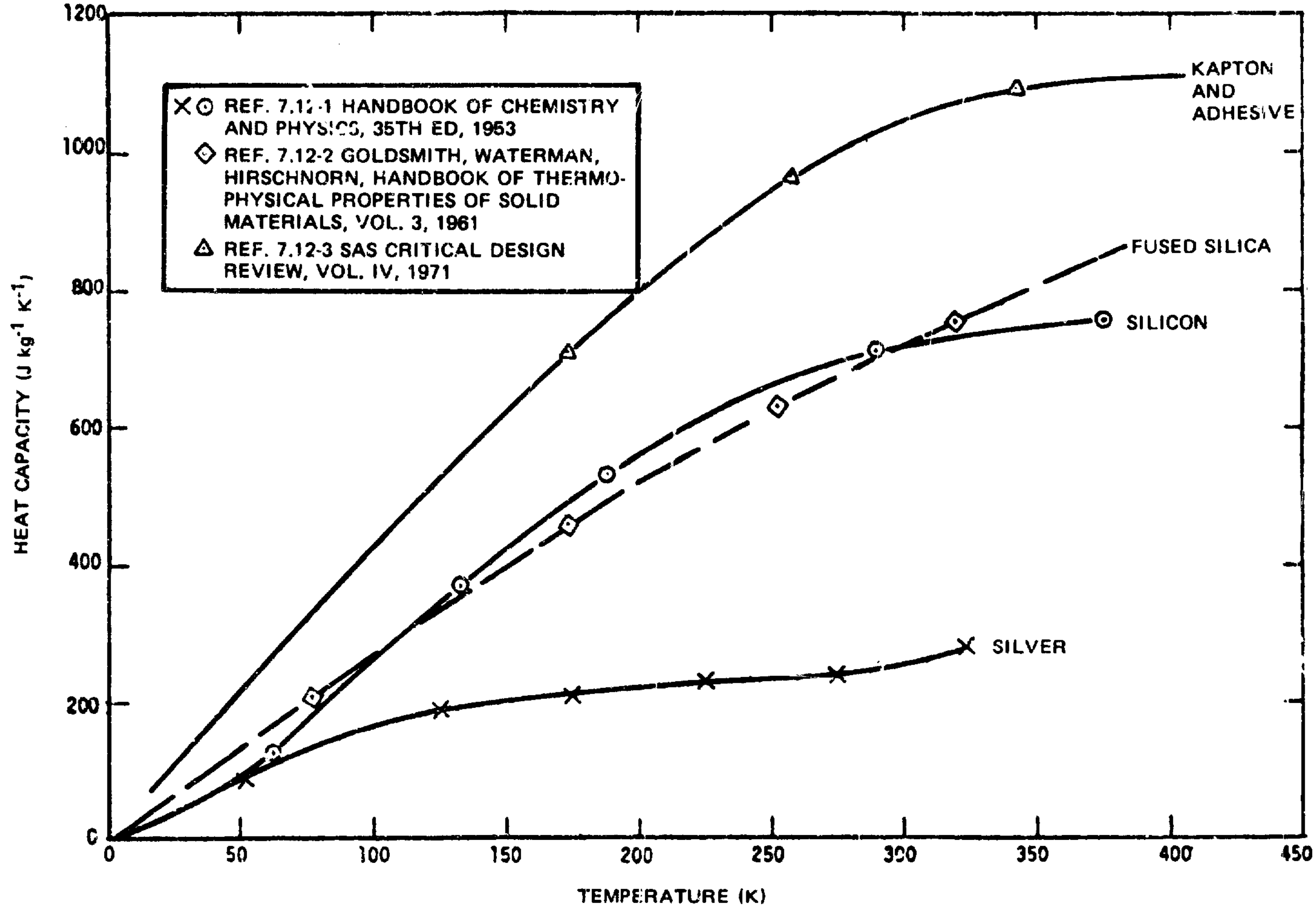


Figure 7.12-1. Specific Heat Capacity for Various Materials

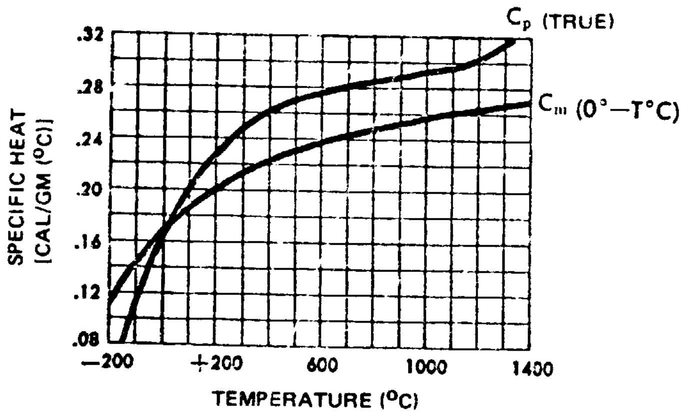


Figure 7. 12-2. Specific Heat Capacity of Fused Silica (Ref. 7. 12-4)

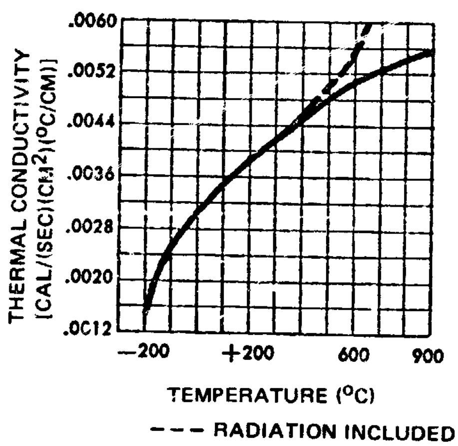


Figure 7. 12-3. Thermal Conductivity of Fused Silica (Ref. 7. 12-4)

7.13 TRANSMISSION, REFLECTION, AND ABSORPTION OF LIGHT

The following data is included in this section:

- Figure 7.13-1. Transmission of Corning 0211 Microsheet
- Figure 7.13-2. Transmission of Corning 7940 Fused Silica (surface reflections included)
- Figure 7.13-3. Transmission of FEP-Teflon
- Figure 7.13-4. Transmission of DC R6-3488 and DC R6-3489
- Figure 7.13-5. Transmission of Cerium Stabilized Microsheet
- Figure 7.13-6. Spectral Reflectance of Cerium Stabilized and Conventional Microsheet Covers Mounted to TiO_x coated Silicon Solar Cells
- Figure 7.13-7. Transmission of Cerium Stabilized and Fused Silica Covers
- Figure 7.13-8. Transmission of Cerium Stabilized and Conventional Microsheet Covers

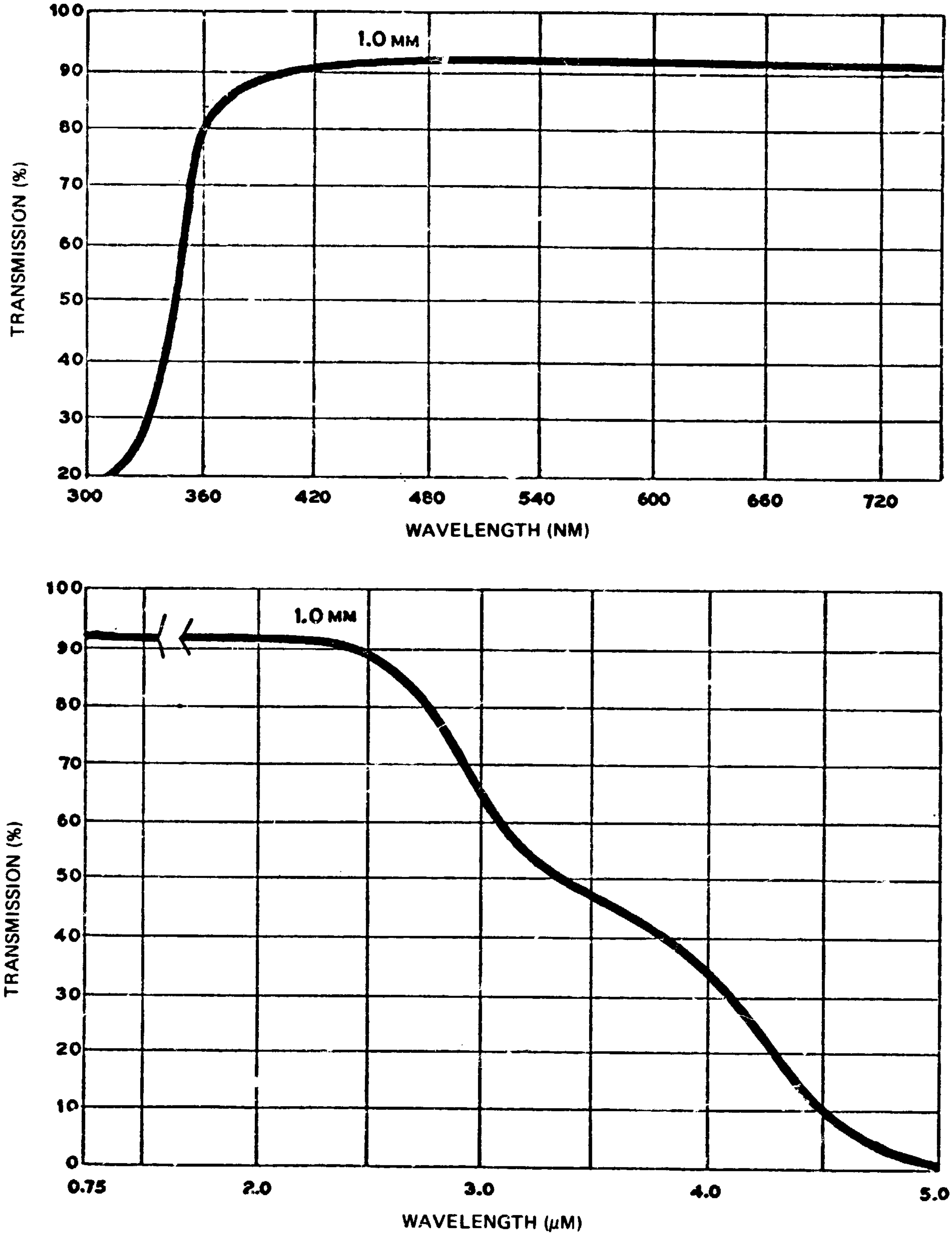
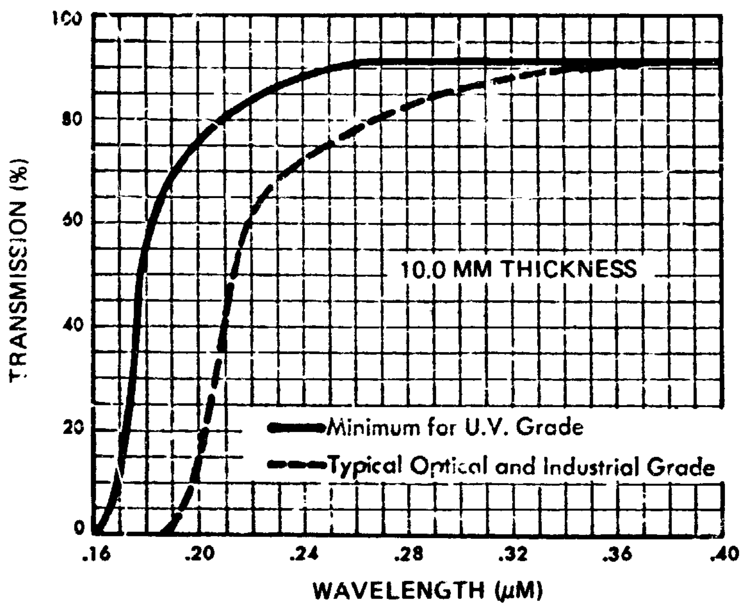


Figure 7. 13-1. Transmission of Corning 0211 Microsheet (Ref. 7. 13-2)



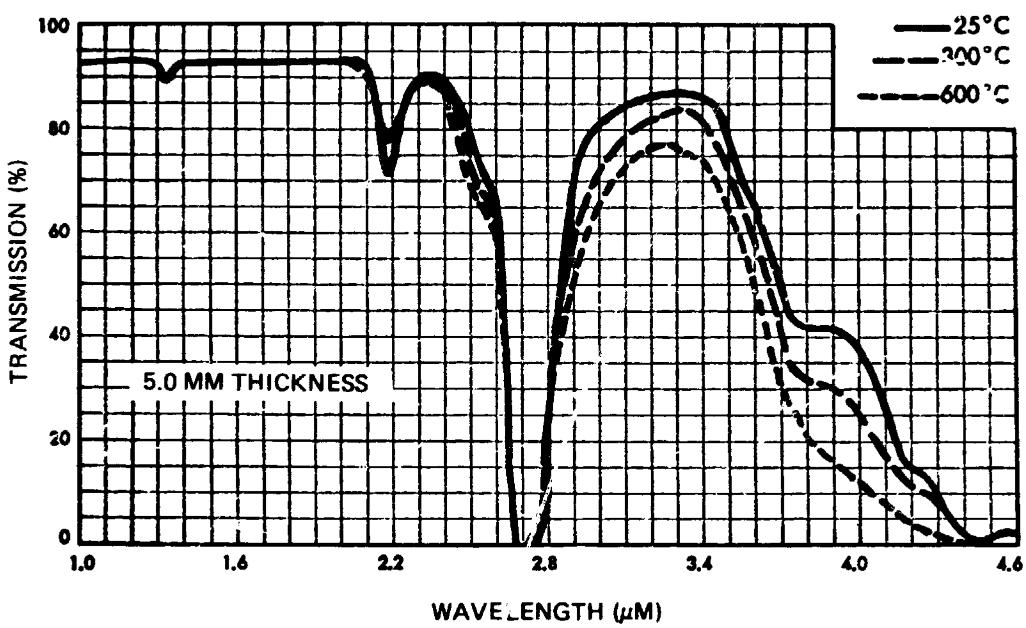
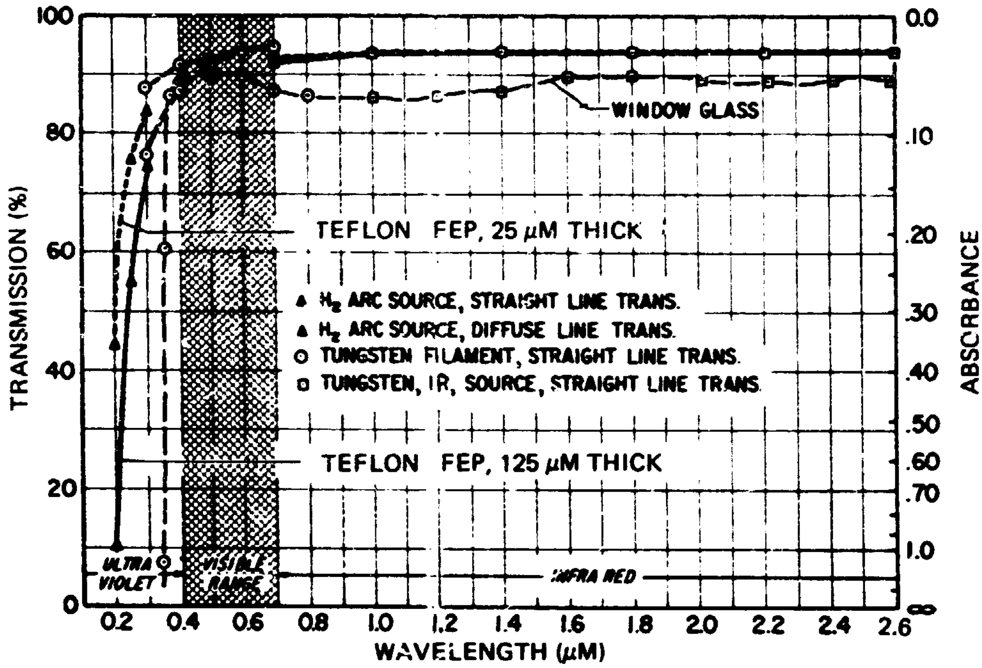


Figure 7.13-2. Transmission of Corning 7940 Fused Silica (surface reflections included) (Ref. 7.13-3)

a. 0.1 to 2.6 µM



*Du Pont's registered trademark

b. 2.5 TO 15 µM

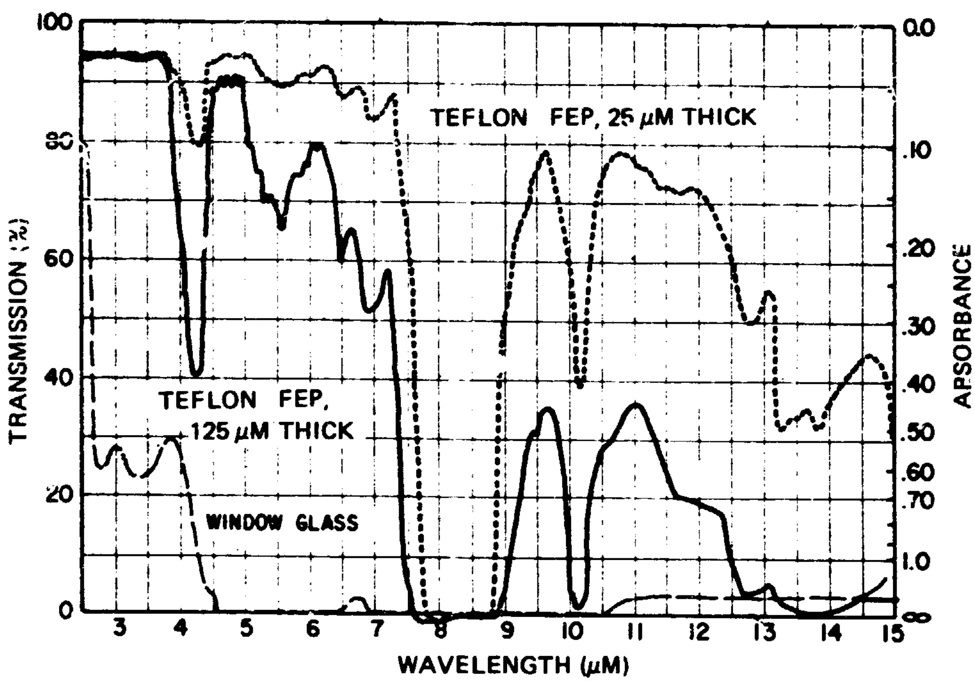


Figure 7.13-3. Transmission of FEP-Teflon (Ref. 7.13-1)

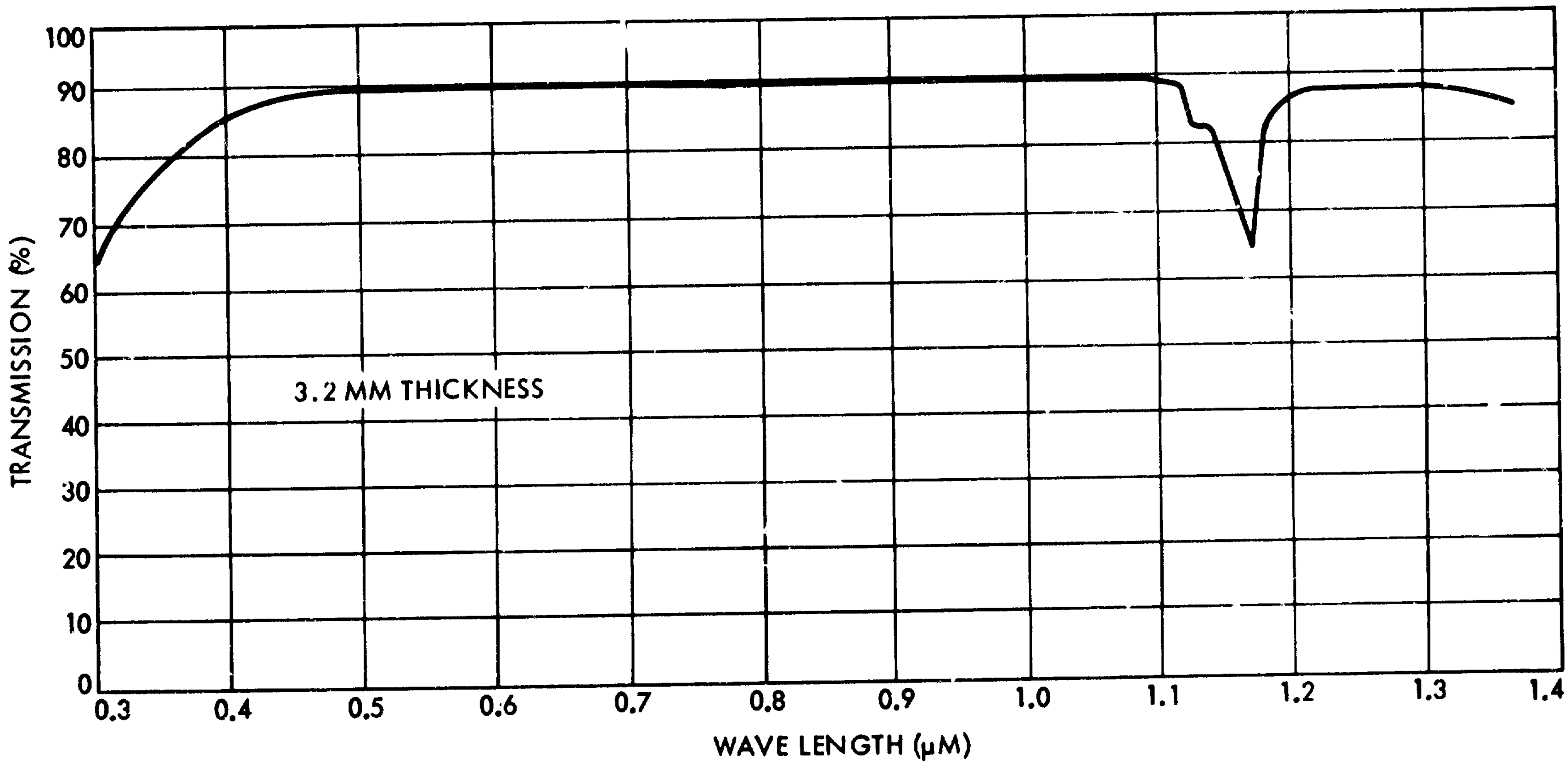


Figure 7.13-4. Transmission of DC R6-3488 and DC R6-3489 (Ref. 7.13-4)

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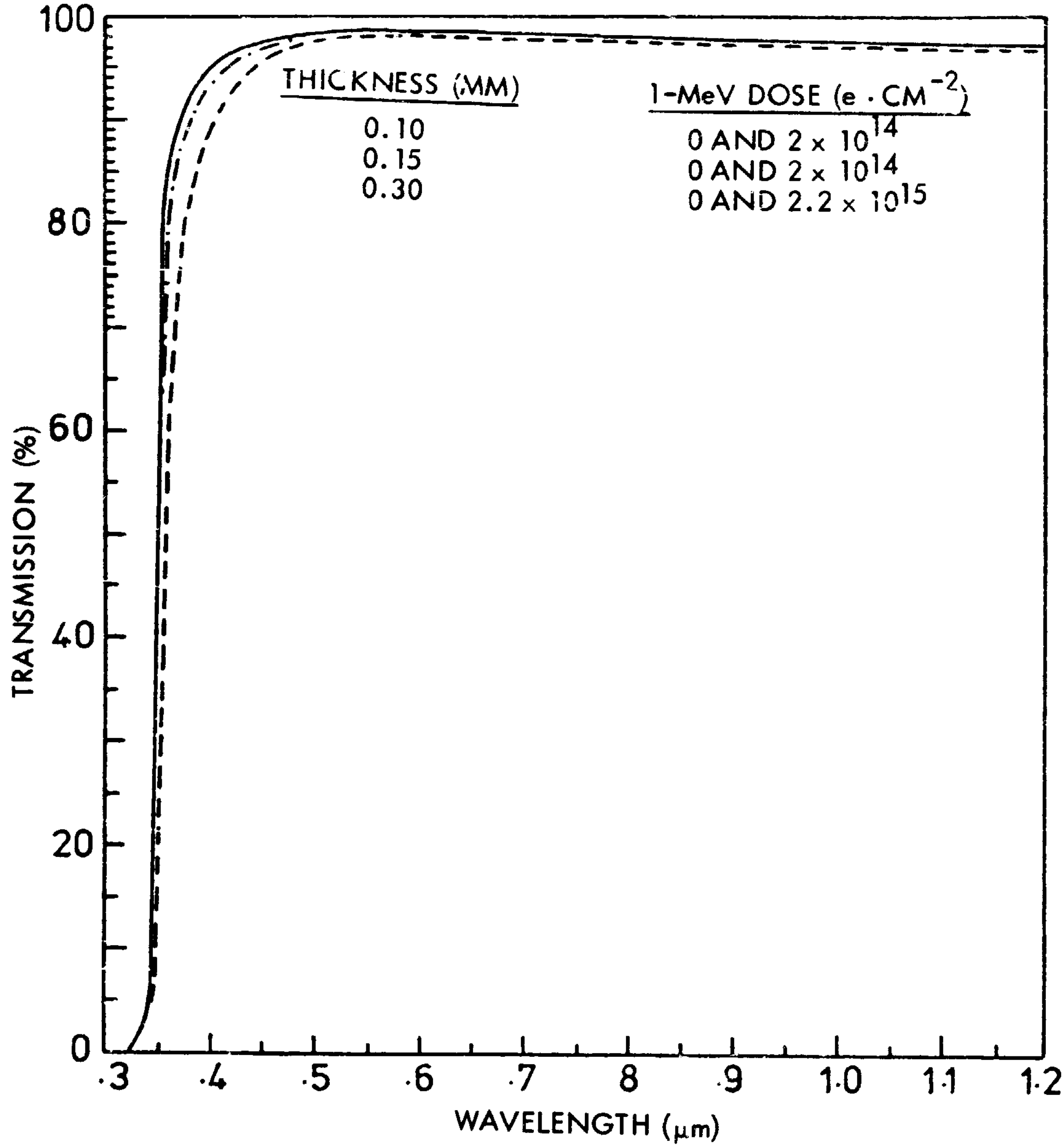

Figure 7.13-5. Transmission of Cerium Stabilized Microsheet Before and After Irradiation (no change in transmission due to radiation; from Ref. 7.13-5).

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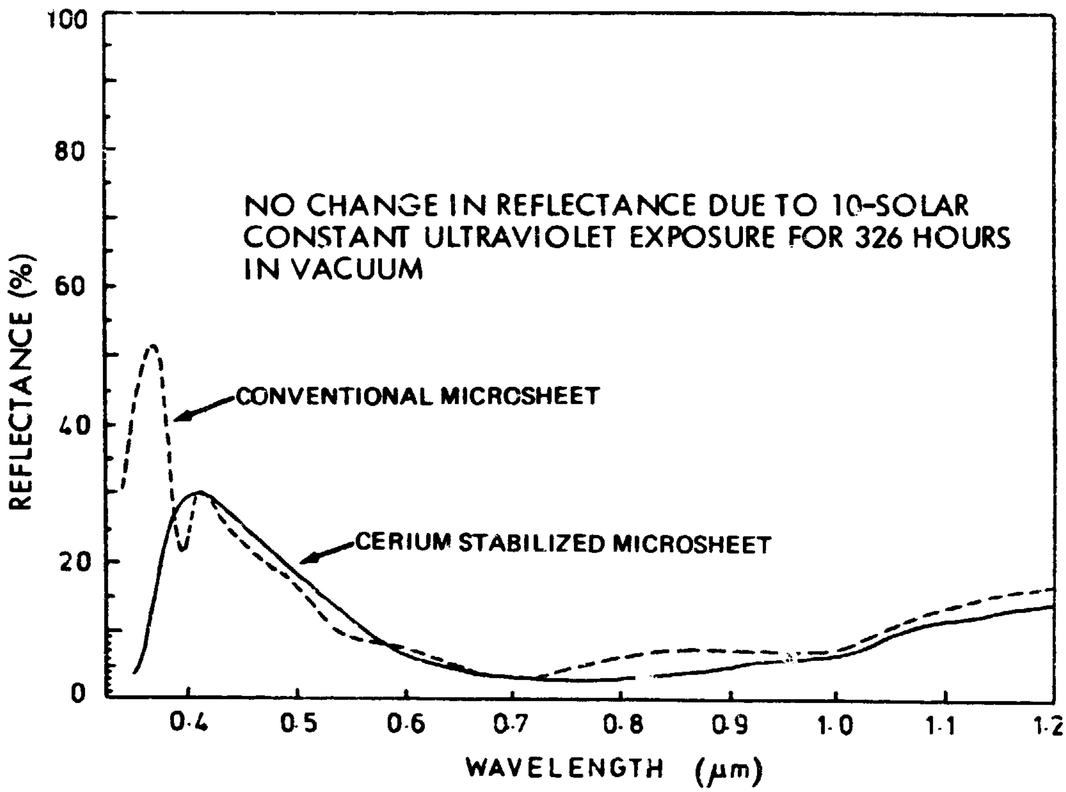

Figure 7.13-6. Spectral Reflectance of Cerium Stabilized and Conventional Microsheet Covers Mounted to TiO_x Coated Silicon Solar Cells Before and After Ultraviolet Exposure (Ref. 7.13-5)

From Ref. 7.13-5. Reprinted with permission of the IEEE.

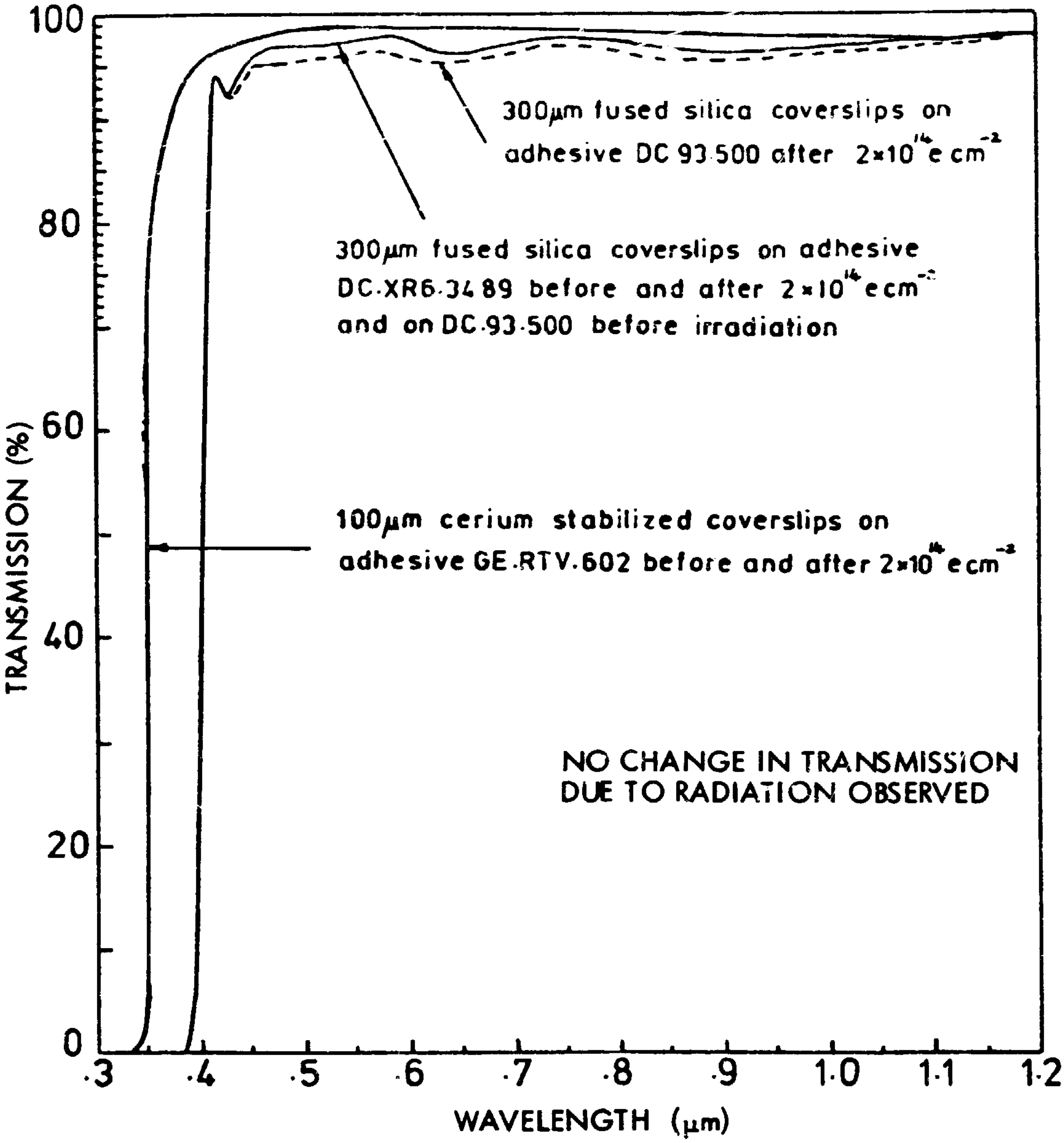

Figure 7. 13-7. Transmission of Cerium Stabilized and Fused Silica Covers (Ref. 7. 13-5)

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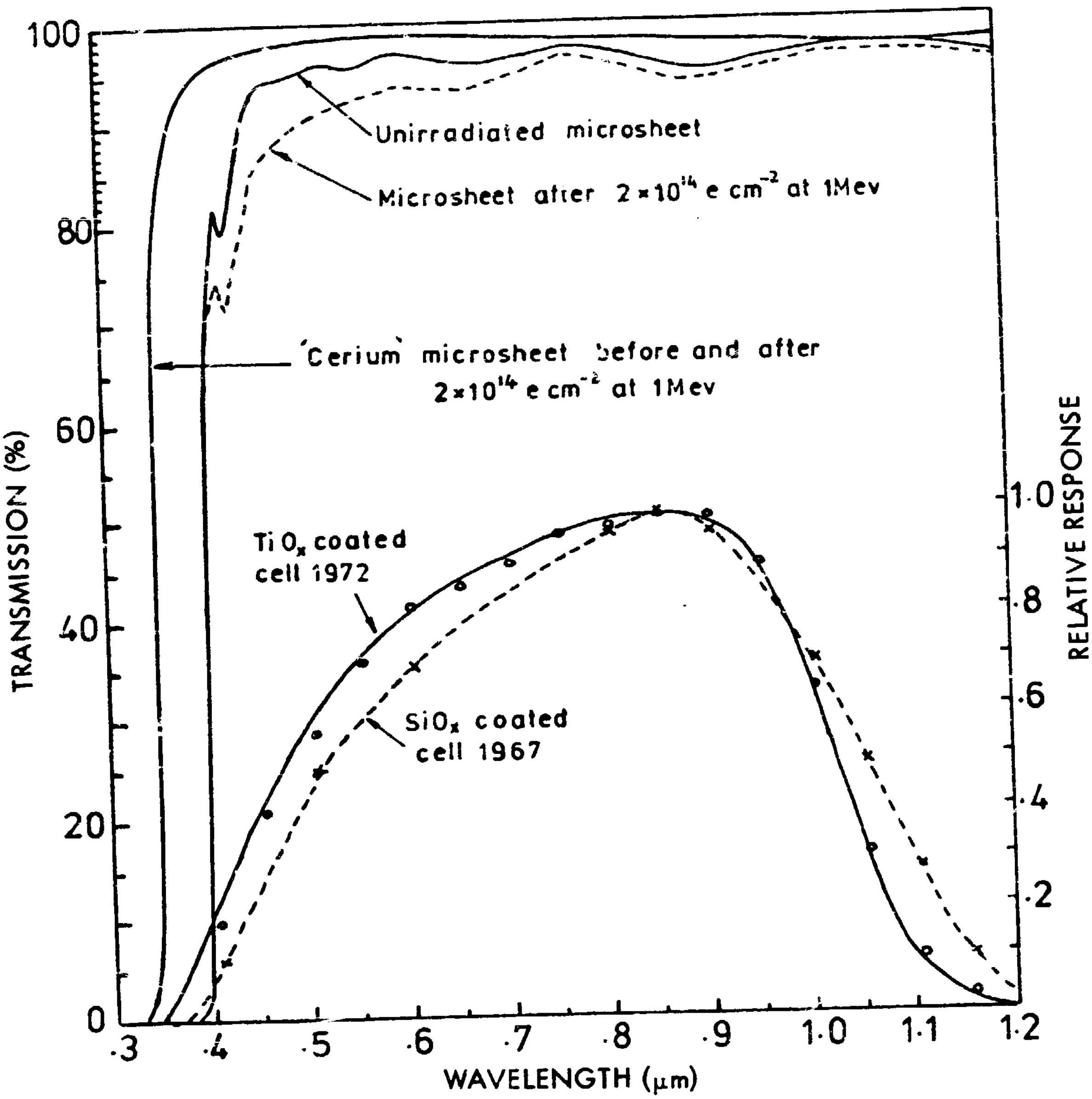

Figure 7.13-8. Transmission of Cerium Stabilized and Conventional Microsheet Covers and Relative Spectral Response of TiO_X and SiO_X Coated, Cerium Stabilized Microsheet Covered Solar Cells (Ref. 7.13-5)

7.14 EMISSION AND ABSORPTION OF HEAT

The following data is presented in this section:

- Figure 7.14-1. Effective Front Surface Emittance of Test Modules
- Figure 7.14-2. Hemispherical Emittance of Kapton on Aluminum Versus Kapton Thickness
- Figure 7.14-3. Hemispherical Emittance of Kapton on Aluminum Versus Temperature
- Figure 7.14-4. Normal Emittance for FEP-Teflon at 38°C Versus Teflon Thickness
- Figure 7.14-5. Hemispherical and Normal Emittance of Typical Epoxy Paints at Room Temperature Versus Dry Paint Thickness
- Figure 7.14-6. Hemispherical Emittance of Cat-A-Lac Paints Versus Temperature
- Figure 7.14-7. Spectral Normal Emissivity of Corning Fused Silica Code 7940
- Table 7.14-1. Emittance and Absorptance of Glassed Solar Cells

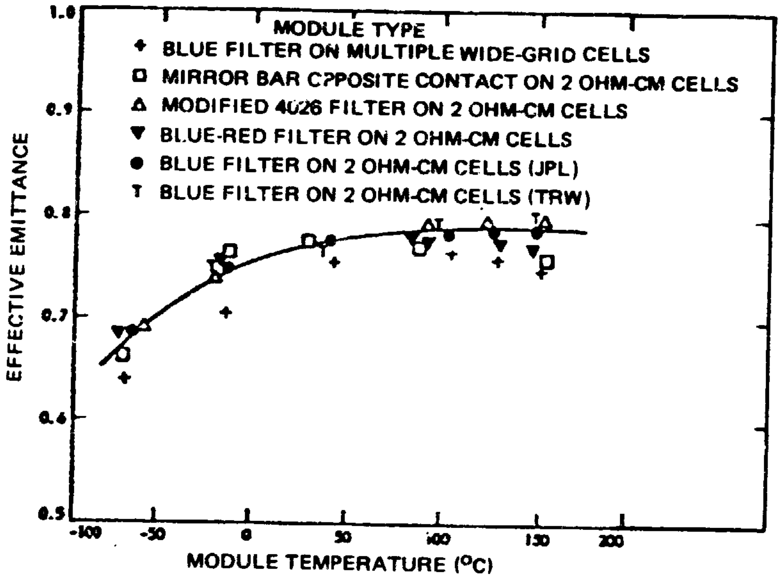

Fig. 7.14-1. Effective Front Surface Emittance of Test Modules (Ref. 7.14-1)

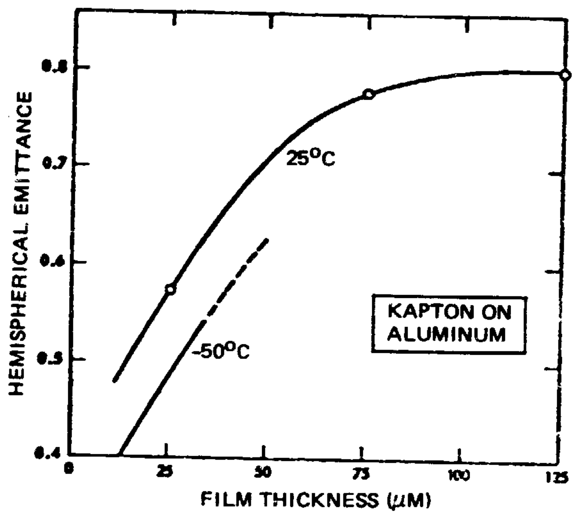

Fig. 7.14-2. Hemispherical Emittance of Kapton on Aluminum Versus Kapton Thickness (Ref. 7.14-2)

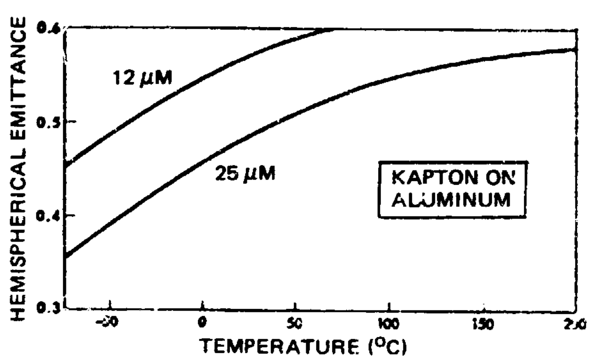

Fig. 7.14-3. Hemispherical Emittance of Kapton on Aluminum Versus Temperature (Ref. 7.14-2)

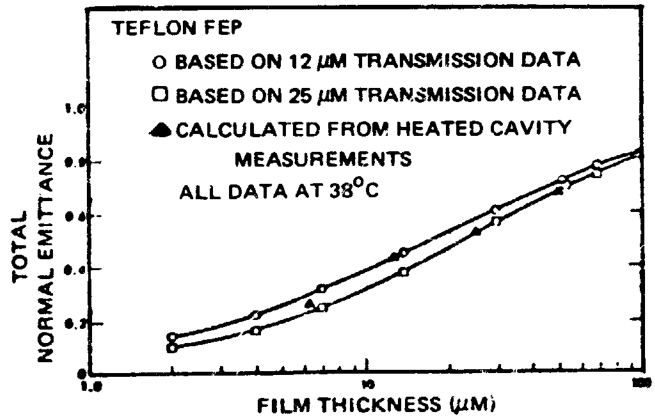

Fig. 7.14-4. Normal Emittance for FEP-Teflon at 38°C Versus Teflon Thickness (Ref. 7.14-3)

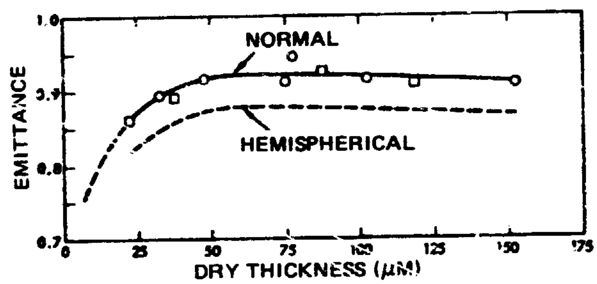

Fig. 7.14-5. Hemispherical and Normal Emittance of Typical Epoxy Paints at Room Temperature Versus Dry Paint Thickness (Ref. 7.14-2)

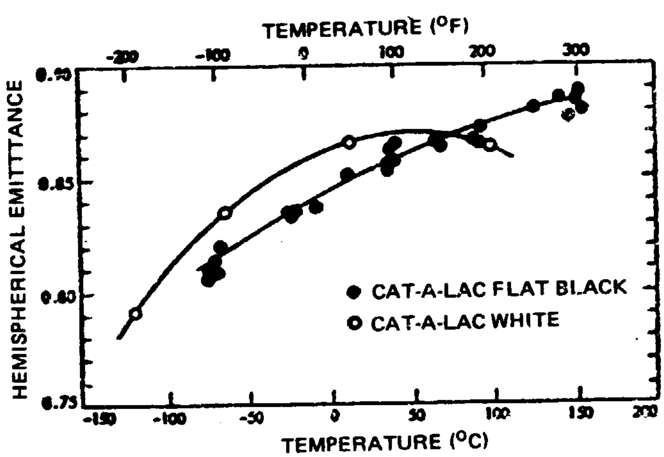

Fig. 7.14-6. Hemispherical Emittance of Cat-A-Lac Paints Versus Temperature (Ref. 7.14-1)

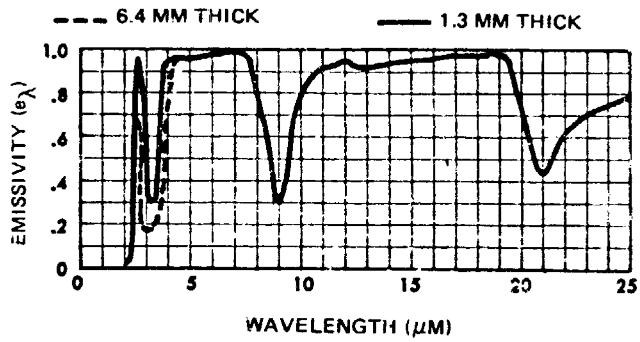

Figure 7.14-7. Spectral Normal Emissivity of Corning Fused Silica Code 7940 (Computed from Room Temperature Measurements of Transmittance and Reflectance — Uniformly Heated Plates) (Ref. 7.14-5)

Table 7.14-1. Emittance and Absorptance of Glassed Solar Cells

Manufacturer	Silicon Solar Cell			Solar Cell Cover			Solar Absorptance	Hemispherical Emittance	α_s/ϵ_H	Ref.
	Type	Polarity	Coating	Material	Cut-on (nm)	Thickness (mm)	α_s	ϵ_H		
Unknown	Conventional	N/P	SiO_x	Fused Silica			-	-	0.954	7.14-4
AEG	Conventional	N/P	TiO_x	Fused Silica			0.805	0.825	0.975	7.14-4
AEG				Microsheet			0.850	0.850	1.000	7.14-4
AEG				Cesia Microsheet	~350		0.872	0.850	1.023	7.14-4
Ferranti				Fused Silica			0.805	0.810	0.994	7.14-4
Ferranti				Cesia Microsheet	~350		0.880	0.860	1.025	7.14-4
Unknown	Conventional	N/P	C_eO_2	Fused Silica			-	-	1.006	7.14-4

7.15 MAGNETIC PROPERTIES

Comparative data for several materials is shown in Table 7.15-1. For unit conversion factors see Section 7.1.

Table 7.15-1. Magnetic Properties of Some Materials

Material	Induced Magnetic Flux Density (gauss)		Ref.
	Saturation (B_s)	Retentivity, (B_{rs})	
Alnico Magnet Material	8,000 to 16,000	7,000 to 13,000	7.15-1
Carbon Steel (1%C)	Unknown	9,000	7.15-1
Core Iron	Up to 15,000	4,000 to 9,000	7.15-1, 7.15-2
Kovar	17,000	Unknown	7.15-3
Invar	7,000	Unknown	7.15-3
Copper	0	0	

7.16 OUTGASSING AND WEIGHT LOSS

The data included in this section is shown in Table 7. 16-1.

Table 7.16-1. Outgassing Properties of Some Solar Cell Array Materials (For definition of terms and test method see Section 7.16 in Vol. I)

Material	Mixing Ratio A/B By Weight	Curing Cycle			TML (%)	CVCM (%)	Ref.
		Time (hours) (days)	Temperature (°C)	Environment			
DC 6-1104		7 D	25	Air	0.19	0.01	7.16-1
		24 H	25	Air	0.16	0.04	7.16-2
DC 93-500	10/1	7 D	25	Air	0.16	0.00	7.16-1
		24 H	25	Air	0.29	0.00	7.16-1
		4 H	65	Air	0.16	0.00	7.16-2
		8 H	25	Air	0.10	0.01	7.16-2
Silgard 182	10/1	22 H	100	Air	1.10	0.33	7.16-1
		22 H	60	Air	1.03	0.23	7.16-1
		7 D	25	Air	1.09	0.33	7.16-1
Silgard 184	10/1	4 H	65	Air	0.92	0.40	7.16-1
		+24 H	150	Air			
		4 H	65	Air	1.32	0.41	7.16-1
		2 H	170	Air	1.01	0.48	7.16-1
DC 6-3488	10/1	4 H	60	Air	1.42	0.74	7.16-1
		4 H	66	Air	0.83	0.40	7.16-1
		+24 H	110	10^{-3} torr			
		16 H	25	Air	0.99	43	7.16-1
		+4 H	65	Air			
		+24 H	110	10^{-3} torr			

Table 7.16-1. Outgassing Properties of Some Solar Cell Array Materials (Continued) (For definition of terms and test method see Section 7.16 in Vol. I)

Material	Mixing Ratio A/B By Weight	Curing Cycle			TML (%)	CVCM (%)	Ref.
		Time (hours) (days)	Temperature (^{o}C)	Environment			
DC 6-3489	10/1	4 H	60	Air	1.42	0.57	7.16-1
		4 H +24 H	65 110	Air 10^{-3} torr	1.11	0.47	7.16-1
		4 H +48 H	65 110	Air 10^{-3} torr	0.89	0.44	7.16-1
		4 H +69 H	65 130	Air 10^{-6} torr	0.23	0.15	7.16-1
		69 H	130	10^{-6} torr	0.36	0.17	7.16-1
Silastic 140		24 H	25	Air	1.38	0.22	7.16-1
RTV 40/T-12	100/0.1	24 H	25	Air	1.49	0.43	7.16-1
		7 D	25	Air	1.07	0.33	7.16-1
RTV 41/T-12	100/0.1	8 H +4 H	25 50	Air Air	2.06	0.45	7.16-1
		8 H +24 H	25 150	Air Air	1.09	0.60	7.16-1
		8 H +24 H	25 250	Air Air	0.17	0.12	7.16-1
RTV 118		24 H	25	Air	2.21	1.07	7.16-1
		24 H +24 H	25 125	Air 10^{-6} torr	0.58	0.43	7.16-2
RTV 511/T-12	100/0.5	24 H	25	Air	3.13	0.60	7.16-1
		3 D +16 H	25 177	Air 10^{-5} torr	0.09	0.00	7.16-1

Table 7.16-1. Outgassing Properties of Some Solar Cell Array Materials (Continued) (For definition of terms and test method see Section 7.16 of Vol. I)

Material	Mixing Ratio A/B By Weight	Curing Cycle: Time (hours) (days)	Curing Cycle: Temperature (°C)	Curing Cycle: Environment	TML (%)	CVCM (%)	Ref.
RTV 560	100/0.5	7 D	25	Air	2.52	0.55	7.16-1
RTV 566	100/0.1	24 D	155	Air	0.14	0.02	7.16-1
		7 D	25	Air	0.07	0.00	7.16-1
	100/0.2	7 D	25	Air	0.27	0.00	7.16-1
	100/0.3	24 H	25	Air	0.34	0.00	7.16-1
	100/0.5	24 H	25	Air	0.41	0.01	7.16-1
		24 H	25	Air	0.29	0.11	7.16-2
RTV 567	100/0.3	12 D	25	Air	0.18	0.07	7.16-1
	100/0.5	12 D	25	Air	0.27	0.07	7.16-1
	100/0.1	48 H	25	Air	0.13	0.01	7.16-1
RTV 577/T-12		48 H	25	Air	2.99	0.57	7.16-1
RTV 580/T-12	100/0.1	24 H	25	Air	1.81	0.81	7.16-1
		+24 H	150	Air			
RTV 602/SRC	100/0.25	24 H	25	Air	3.10	0.96	7.16-1

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